

ESSAYS ON FOREIGN TREASURY PURCHASES AND THE YIELD CURVE

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Abstract

A growing literature finds that large purchases of US Treasury debt by foreign investors lower Treasury yields. However, this literature does not adequately address the endogeneity of foreign Treasury purchases to yields. The first two chapters of this dissertation overcome this identification problem with two different methods and therefore identify larger impacts of purchases than previous studies. The third chapter improves the measurement of foreign Treasury purchases.

In the first chapter, I analyze the dynamic impacts of foreign Treasury purchases on yields in the context of a sign-identified vector autoregression. In the baseline results, a surprise foreign purchase of \$100 billion of US Treasury securities significantly lowers all yields for approximately two years. The largest impacts occur after about one year, with yields lower by 70 to 100 basis points. Additionally, I decompose long rates, revealing that the Federal Reserve acts to lessen the impact of foreign purchases, but not enough to offset large declines in term premia. My estimated effects of purchases on yields are generally larger than those found elsewhere and indicate both that foreign Treasury purchases explain the period of low rates in the 2000s and that LSAPs have substantial impacts on yields.

The second chapter uses a novel measure of surprise foreign official Treasury purchases, high frequency data, and the technique of identification by heteroskedasticity to identify the effect of Chinese official purchases of US Treasury securities on yields. The effects I estimate are statistically significant and on the same order of magnitude as the lower frequency findings in the first chapter of the dissertation.

In the third chapter, I address shortcomings in the existing data on cross-border Treasury flows. Sources of raw data are noisy, inconsistent, and available only at lower

frequencies, while existing techniques for improving this data use a limited information set. I estimate a new measure of net foreign Treasury flows as an unobserved state variable using the Kalman filter, with raw flows data, yields, and exchange rates as observables. The resulting time series of net flows addresses the above shortcomings and highlights several instances where existing data sources were misleading.

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CHAPTER 1

Foreign Treasury Purchases and the Yield Curve: Evidence from a Sign-Identified Vector Autoregression

1.1 Introduction

In the mid-2000s, interest rates on long-term Treasury securities appeared unusually and persistently low. As the Federal Reserve raised the federal funds rate in the second half of 2004, long-term interest rates actually declined. As short rates rose, nominal and real forward rates fell (Backus and Wright (2007)). This behavior seemed strange given the historical behavior of the yield curve, and Federal Reserve Chairman Alan Greenspan (2005) labeled it a “conundrum.” Moreover, this anomalous behavior was only a particularly remarkable episode during a much longer period of oddly low interest rates. Empirical studies tend to find that long-term Treasury yields were unusually low given the state of the business cycle, the stance of monetary policy, and inflation expectations through much of the 2000s. As a rule of thumb these studies estimate that the yield on the 10-year note was perhaps 50-80 basis points lower than might have been expected based on its historical behavior.

Of course, the mid-2000s were also a time when foreigners, especially the central banks of emerging Asian economies, were buying large quantities of US debt. Some policymakers, such as Bernanke (2005) and Greenspan himself, have suggested that these large capital flows may be the cause of the “bond yield conundrum.” This

explanation for the conundrum requires that the quantities of outstanding financial assets exert substantial influence on the prices and yields of those assets. This topic is doubly important given the large scale asset purchases undertaken by many central banks in the wake of the recent financial crisis. Indeed, the motivation for such asset purchase programs offered by many central bankers is precisely that by reducing the outstanding quantity of financial assets, usually government debt, they expect to lower yields. There is a growing literature studying the effects of Treasury purchases on yields, whether the purchasers are foreigners or domestic central banks. However, this literature faces a difficult econometric task in identifying the effects of the purchases.

This paper asks whether and to what extent foreign purchases of Treasury securities affect Treasury yields, and it does so in the context of a sign-identified vector autoregression (VAR). The variables in the VAR are net foreign purchases of US Treasury securities and the first three factors of the yield curve.

In the baseline results, I find that an exogenous purchase of \$100 billion of Treasury securities by foreigners in a single month significantly lowers Treasury yields across the term structure for around two years following the purchases. As rough guide, the 1- and 5-year yields decline by perhaps 90 to 100 basis points, while the ten-year yield declines by about 70 basis points, with the largest impacts coming a year or more after the purchase.

Decomposing long-term interest rates into term premia and expected future short rates, I find evidence that the Federal Reserve responds conservatively to foreign purchases, allowing purchases to cause a significant loosening of credit conditions. The responses of 5- and 10-year yields reflect a response of term premia which is larger and more persistent than the response of yields overall, combined with a small rise in the average of expected future short rates. The Fed does tighten policy in response to the compression of term premia, but does not do so aggressively enough to fully offset the impacts of the purchases on yields. By failing to prevent a loosening

of credit conditions in response to large foreign purchases of US financial securities, the Fed might allow asset price bubbles to grow. This assertion is at least consistent with the fact that the US experienced a bubble in a sector known to be very sensitive to long-term interest rates (real estate) in the mid-2000s; the mid-2000s were also a period of large foreign purchases of US securities and oddly low long rates.

The fundamental obstacle in identifying the effects of foreign Treasury purchases on yields is that foreign Treasury purchases are endogenous to yields. Clearly, *private* foreign Treasury purchases are endogenous to yields; private investors make their Treasury purchases with the price or yield of the securities in mind. Any reasonable theory of portfolio allocation would suggest they should. In spite of this fact, no existing studies have addressed the endogeneity of private foreign purchases. Where private purchases have been considered, they have been assumed to be exogenous to yields, for the lack of a credible identification method.

Foreign *official* purchases of Treasuries are also endogenous. Survey and anecdotal evidence suggests that official reserve managers behave in much the same manner as private investors, engaging in optimal portfolio allocation (Borio, Galati, and Heath (2008) and Papaioannou, Portes, and Siuourounis (2006)). Further, even if one ignores the fact that official reserve managers are portfolio optimizers, Treasury purchases made in pursuit of exchange rate targets are endogenous to yields. A simple example illustrates this point. Suppose that the Federal Reserve unexpectedly raises the federal funds rate, shifting the level of the yield curve upward and raising the value of the dollar. To foreign central banks, this corresponds to a weakening of their domestic currencies. Those central banks maintaining below-equilibrium nominal exchange rate pegs, as China did at least during the mid-2000s, will now need to purchase fewer Treasuries to maintain the weakness of their currencies. In this example, causation runs from yields to official purchases, not the other way around. Thus, foreign official Treasury purchases are endogenous to yields. Overcoming this endogeneity in both

private and official Treasury purchases requires an identification scheme.

Researchers have used two broad approaches to overcome the endogeneity of foreign purchases, but neither is fully satisfactory. The dominant approach is the event study. By focusing on the behavior of Treasury yields in short periods of time, of a few days or less, around either actual foreign Treasury purchases or announcements regarding future purchases, the event study methodology can attenuate the bias induced by endogeneity. For example, Chapter 2 of this dissertation examines the behavior of yields within 2-hour windows around surprise announcements regarding Chinese exchange rate policy. These are also surprises regarding future Chinese official Treasury purchases, since purchases of dollar-denominated assets (mostly Treasuries) are the mechanism by which the exchange rate is managed. The identifying assumption is that the policy surprises cause the large moves in yields seen immediately after the surprise. The tight chronological ordering argues in favor of causality running from purchases to yields (rather than from yields to purchases) and the narrow observation windows argue in favor of ruling out omitted variables. Bernanke, Reinhart, and Sack (2004) and Abe (2007) are other studies using broadly similar event study methods in evaluating foreign purchases. This methodology is also very widely used in the related literature on the recent large scale asset purchases in response to the financial crisis (Gagnon, Raskin, Remache, and Sack (2010), Krishnamurthy and Vissing-Jorgensen (2011), and Wright (2012), among many others).

The event study methodology has two major drawbacks, however. First, there are relatively few discrete events to study, leading to concerns regarding small samples. Second, event studies cannot provide estimates of the dynamic impact of foreign purchases; they must focus on narrow periods of time to achieve identification. As a result, generalizing the findings of event studies to economically meaningful periods of time requires additional assumptions.

The second broad approach to the identification problem has been to use instru-

mental variables. Conditional on finding valid and strong instruments, this approach is a promising solution to the identification problem. However, finding satisfactory instruments is challenging. Beltran, Kretchmer, Marquez, and Thomas (2012) report some success in finding instruments for foreign official purchases, but not for private purchases.¹ This forces them to separate flows into official and private flows, which is undesirable given the limited ability of the data to accurately distinguish between the two (see Bertaut and Tryon (2007) for more on this topic). Further, lacking valid instruments, they must assume that private purchases are exogenous. This is a questionable identifying assumption.

I employ a sign-identified VAR to assess the impacts of foreign Treasury purchases on yields because this methodology offers several improvements over the alternatives. First and foremost, it allows me to achieve identification, albeit set identification, with a relatively well-understood identification scheme and without imposing economically indefensible identifying restrictions. Further, it makes the restrictions that I do apply much more transparent, allowing for meaningful discussion of them. Second, unlike an event study, this approach allows me to estimate of the dynamic impacts of foreign Treasury purchases on yields. In the Results section, I report impulse responses of the factors of the yield curve, of individual yields, and of term premia over a 5-year horizon. These confidence intervals exclude zero over a wide range of horizons. Third, as this last point suggests, I can straightforwardly characterize the impact of purchases on yields over economically meaningful horizons. Fourth, by employing a VAR in the factors of the yield curve, I can parsimoniously summarize the impact on the entire yield curve. Finally, by estimating the dynamic response of the entire yield curve, I am able to decompose the behavior of yields into the responses of term premia and expected future short rates. There is very little empirical evidence on the behavior of the individual components of yields following purchases, either

¹See also Sierra (2010).

purchases by foreigners or by domestic central banks. My results suggest that this decomposition of yields is informative and has important implications for the impacts of purchases.

The paper is organized as follows: Section 1.2 discusses the empirical model and the technique of sign-identification in detail, while comparing this empirical methodology to relevant alternatives. Section 1.3 motivates the identifying restrictions that I use. Section 1.4 presents the empirical results and discusses the trade-offs between the strength of the results and the strength of the identifying restrictions. Section 1.5 concludes.

1.2 Empirical Methodology

In this section, I will describe the model and the data I use, argue that this model is well-suited to assessing the impact of purchases on yields, and discuss the technique of sign identification.

1.2.1 VAR Specification

To identify the effects of foreign Treasury purchases on Treasury yields, I employ a monthly, 4-variable VAR of lag order 12:

$$\begin{aligned} y_t &= a + A_1 y_{t-1} + A_2 y_{t-2} + \dots + A_{12} y_{t-12} + u_t \\ &= a + \sum_{j=1}^{12} A_j y_{t-j} + u_t, \end{aligned} \tag{1.1}$$

where

$$y_t = \begin{bmatrix} \text{flows}_t \\ \text{level}_t \\ \text{slope}_t \\ \text{curvature}_t \end{bmatrix} = \begin{bmatrix} f_t \\ l_t \\ s_t \\ c_t \end{bmatrix},$$

$u_t \sim \mathcal{N}(0, \Sigma)$, and a is a column vector of constants.

The variable *flows* is the accumulation of the monthly net purchases of Treasury securities by all foreign agents over the preceding 12 months. I use accumulated capital flows as a straightforward way to smooth the highly volatile monthly data and also to make my results more comparable to other studies, which also smooth the data in this way. Because the flows variable exhibits twelfth-order autocorrelation by construction, I choose the lag order of the VAR to be 12.

My choice of the monthly data used to construct the accumulated *flows* variable is motivated by the quality of available monthly data. Broadly, the raw monthly flows data, from the Treasury International Capital (TIC) surveys have three problems. First, the Treasury conducts monthly flows surveys and annual holdings (stocks) surveys, and these two surveys produce inconsistent results. To address this shortcoming of the data, I use TIC data adjusted as in Bertaut and Tryon (2007). As is conventionally done in the literature, Bertaut and Tryon assume that the comprehensive annual surveys of holdings are accurate. This assumption is plausible, given the more detailed nature of the annual holdings surveys. They then adjust the raw monthly flows data to make them consistent with the annual surveys by, for example, accounting for otherwise ignored valuation changes. This adjustment gives a series for net Treasury purchases that is consistent across survey measures.

The other two shortcomings of the data are harder to overcome. The second shortcoming of the data is poor attribution of net purchases to the type of purchaser (official versus private) and the third is poor attribution to the nationality of the

purchaser. Bertaut and Tryon (2007) offer an ad hoc solution to these two problems, but admit that they are harder to address than the first issue. Because of these data limitations, I do not disaggregate the data by type or nationality of purchaser. I focus on total net foreign purchases, adjusted as in Bertaut and Tryon (2007).

The variables *level*, *slope*, and *curvature* are the first three factors of the yield curve. They are named according to the convention dating to Litterman and Scheinkman (1991). I follow results in Ang and Piazzesi (2003), Diebold and Li (2006), and Diebold, Rudebusch, and Arouba (2006) and define the yield curve factors as linear combinations of yields. Specifically, denoting the j -year yield at time t by $i_{j,t}$, I define the factors as follows:

$$\begin{aligned}\text{level}_t &= \frac{i_{1,t} + i_{5,t} + i_{10,t}}{3} \\ \text{slope}_t &= i_{10,t} - i_{1,t} \\ \text{curvature}_t &= 2i_{5,t} - (i_{1,t} + i_{10,t})\end{aligned}$$

Such linear combinations of yields have been shown by other studies, including those mentioned above, to behave very much like the latent factors derived from formal term structure models. While the precise maturities of the yields chosen tend to vary from study to study, my results are robust to alternative choices. For the individual yields, I use the monthly average of nominal, daily, and continuously compounded zero-coupon Treasury yields from Gürkaynak, Sack, and Wright (2006).

I use data from January 1985 through June 2011, based on the availability of revised cross-border Treasury flows data, which is available only with a substantial lag. Finally, note that the ordering of the variables in y_t is irrelevant, as I am not using ordering restrictions for identification.

1.2.2 Rationale For This Specification

As discussed in the introduction to the paper, there are several reasons for using a VAR to assess the impacts of foreign Treasury purchases on Treasury yields. In short, a VAR allows for the use of sensible, relatively well-understood identification techniques to parsimoniously estimate the dynamic impacts of purchases on the entire yield curve.

A macro-finance term structure model (MTSM), of the sort in Ang and Piazzesi (2003), is an alternative approach, but I do not use such a model for two reasons. First, one might suppose that an MTSM would give more rigorous results because it brings the power of asset pricing theory to the data. Specifically, the no-arbitrage condition assumed in such models provides restrictions on the elements of the VAR slope matrices (the A 's above). However, Joslin, Le, and Singleton (2013) show theoretically and in the context of illustrative examples that these restrictions provide little benefit. The results from a much simpler VAR in the factors the yield curve, as I implement here, are very nearly identical to the results from much more sophisticated term structure models. Second, the more complicated structure of MTSMs would require that the econometric identification techniques be more complex and less well-understood. In MTSMs, the evolution of the factors of the yield and of the individual yields are modeled with separate equations. This fact would make the imposition of, say, sign restrictions challenging. One cannot sensibly restrict the behavior of individual yields without restricting the evolution of the factors of the yield curve. How one might impose consistent restrictions across the equations is not well-understood. In any event, MTSMs offer little benefit, regardless of whether the identification problem is solved.

A potential issue with my model is the topic of unspanned factors of the yield curve. As discussed in Duffee (2011) and Joslin, Pribsch, and Singleton (2010),

the assumptions underlying standard asset pricing theory imply that all information relevant to the current state and future behavior of the yield curve is captured in bond yields today. If this is not true, bonds are mispriced. If it is true, then any variable known at time t that is not derived from the yield curve, including foreign purchases of Treasuries, should have no predictive power for yields from time t forward. Only in a knife-edge parameterization of asset pricing models might such a variable, referred to as an unspanned factor of the yield curve, have any true predictive power for future yields.

However, while a model which includes only the factors of the yield curve might be expected to fit the data better, such a model is not especially interesting from a macroeconomic perspective. I am interested in examining the impact of Treasury flows on yields, not the impact of yields on yields. My specification allows me to estimate the structural impulse responses of a shock to flows on the yield curve. The fact that the model might also be interpreted as a model of four factors of the yield curve, one of them unspanned, is potentially interesting. However, it is not relevant to the question at hand.

1.2.3 The VAR Identification Problem

To provide context for later discussion of the identifying restrictions and to provide background on the identification technique, I will now briefly explain the identification problem with VARs and how sign identification addresses it.

First, consider a general structural VAR model of a form comparable to the reduced form model in Equation (1.1). Such a model can be written as

$$B_0 y_t = b + \sum_{j=1}^{12} B_j y_{t-j} + \varepsilon_t, \quad (1.2)$$

where y_t is an 4×1 vector as discussed above, b is an 4×1 vector of constants, B_j

is 4×4 , and $\varepsilon_t \sim \mathcal{N}(0, I)$. That fact that B_0 is allowed to be anything besides a diagonal matrix leaves open the possibility of contemporaneous interaction among the variables. That is, it allows for endogeneity.

This model can be rewritten as

$$y_t = B_0^{-1}b + \sum_{j=1}^{12} B_0^{-1}B_j y_{t-j} + B_0^{-1}\varepsilon_t, \quad (1.3)$$

$$= a + \sum_{j=1}^{12} A_j y_{t-j} + u_t, \quad (1.4)$$

where the second line is clearly the reduced form model. Ordinarily, the economist does not know the structural model. That is, he does not know the values of B_j , $j = 0, 1, \dots, 12$. In particular, because he does not know B_0 , he does not know the nature of the endogeneity and so cannot directly overcome it. While he does not know B_0 , he does know that $\text{Var}(\varepsilon_t) = I$ by assumption, and so he knows that

$$\text{Var}(u_t) = \Sigma = B_0^{-1} (B_0^{-1})' = \text{Var}(B_0^{-1}\varepsilon_t).$$

Now, Σ is estimable. However, being a variance-covariance matrix, Σ is symmetric and so has only 10 unique elements (in the case that it is 4×4). On the other hand, B_0^{-1} has 16 unique elements. Thus, there are more unknowns than equations and so there are an infinite number of admissible solutions for B_0^{-1} . In particular, if \bar{B}_0^{-1} is a candidate solution, then so is $\bar{B}_0^{-1}P$ for any orthogonal matrix P . To see this, note that

$$\text{Var}(\bar{B}_0^{-1}P\varepsilon_t) = \bar{B}_0^{-1}PP'(\bar{B}_0^{-1})' = \bar{B}_0^{-1}(\bar{B}_0^{-1})' = \text{Var}(\bar{B}_0^{-1}\varepsilon_t),$$

where the second equality follows from the orthogonality of P . Thus, without further restrictions, the economist cannot identify a unique B_0^{-1} which is associated with a unique structural model. Without knowing B_0^{-1} , the economist cannot assess the impact of the structural shocks ε_t on y_t . Specifically, the reduced form errors, u_t , will

be some unknown and economically uninteresting linear combination of the shocks to flows, level, slope, and curvature.

Traditionally, the identification problem is solved by imposing sufficient equality restrictions on the elements of B_0^{-1} to identify a unique matrix and structural model. These restrictions are generally motivated by economic theory, separate empirical evidence, or knowledge of institutional details. Arguably the most common set of restrictions are exclusion restrictions, typically restricting that the above-diagonal elements of B_0^{-1} are zero. In such an identification scheme, the ordering of variables in y_t is important (unlike in this paper). These exclusion restrictions reduce the number of unknowns by precisely enough to identify a unique B_0^{-1} . Such a method is commonly used to identify the effects of monetary policy shocks on output and prices.

Theory and evidence do not support such restrictions in this instance. To make the point clear, I will consider why no element of B_0^{-1} can be subjected to equality restrictions. First, foreign Treasury purchases are certainly endogenous to the contemporaneous yield curve, especially when time is measured in months. To illustrate this point, suppose that the level of the yield curve rises, perhaps because the Federal Reserve raises the federal funds rate. First, portfolio optimizers should be expected to react quickly to changes in asset prices; they should certainly react within the month. Second, changes in the yield curve affect exchange rates almost immediately (see, for example, Faust, Rogers, Wang, and Wright (2007)). Surely, then, foreign central banks pegging to the dollar will change their net purchases of Treasuries within the month. Thus, no element in the first row of B_0^{-1} can be restricted to zero. Since economists do not have precise estimates of the impact of the yield curve on flows at the monthly frequency, no element of the first row of B_0^{-1} can be restricted to any other fixed value, either.

Next, the factors of the yield curve are endogenous to contemporaneous Treasury

purchases. For example, Bernanke, Reinhart, and Sack (2004), Abe (2007), and the second chapter of this dissertation all show that yields respond within no more than a day to Treasury purchases. Chapter 2 shows that yields respond within two hours. Shocks to Treasury flows contemporaneously influence the factors of the yield curve. Further, the impacts are only imprecisely estimated. Thus, the elements of the first column of B_0^{-1} cannot be restricted to particular values, either.

Finally, the factors of the yield curve are endogenous to one another contemporaneously. Given my definitions of the factors, this is almost necessary by pure algebra. More generally, theory and evidence offer no particular value for the contemporaneous effect of, say, the slope of the yield curve on its level. So, the remaining off-diagonal elements of B_0^{-1} cannot be restricted. The diagonal elements can be normalized as the econometrician desires.

Thus, I cannot uniquely identify B_0^{-1} . Strictly speaking, there are of course other techniques to identify a unique B_0^{-1} , such as long-run restrictions (as in Blanchard and Quah (1989)). These alternatives also appear ill-suited to my question because the needed identifying restrictions are difficult to defend.

Although equality restrictions cannot be economically motivated, I can achieve set identification of B_0^{-1} using inequality (sign) restrictions on the impulse response functions.

1.2.4 Sign Identification

In spite of the fact that economic theory and evidence are insufficient to identify a unique structural model, they do provide some guidance as to what a “reasonable” structural model might look like. Sign identification allows me to address the identification problem by limiting the class of structural models to a manageable set of “reasonable” models. This is done by discarding all structural models whose impulse response functions exhibit certain undesirable properties. These restrictions on the

impulse responses are implemented as restrictions either on the signs of the elements of the structural impulse responses or on the signs of linear combinations of those elements. There are many *inequality* restrictions which are economically justifiable, in spite of the fact that there are no justifiable *equality* restrictions.

For concreteness, consider an example. Asset pricing theory and event study evidence suggest that an increase in net foreign Treasury purchases should not raise yields. Indeed, empirical evidence suggests that foreign purchases depress yields, at least temporarily. Thus we might say that any reasonable structural model would be such that a structural shock to Treasury purchases does not raise the level of the yield curve. Based on the same evidence, we might also say that such a shock does not steepen the yield curve. The particular sign restrictions used will be discussed in more detail below, but these should serve as a motivational examples.

These sign restrictions are direct restrictions on the impulse response functions implied by the structural models and are indirect restrictions on the elements of B_0^{-1} . In the case of restrictions on the sign of impulse responses within the period of the structural shock, they are linear inequality restrictions. The numerous other sign restrictions which can be placed on the impulse responses are often complex non-linear restrictions on B_0^{-1} .

Once one chooses a list of sign restrictions to impose on the impulse responses, one only needs to summarize the set of models that satisfy the sign restrictions. I adopt a Bayesian approach to summarizing the models. I assume a uniform prior over the set of rotation matrices and a diffuse prior on the reduced form VAR coefficients.

More specifically, I impose sign restrictions computationally in several steps, following the general methods of Faust (1998) and Uhlig (2005), as modified in Inoue and Kilian (2013):

1. To address estimation uncertainty regarding the reduced form parameters A_j , $j = 1, \dots, 12$, c , and Σ , I draw a large number of them from the posterior

distribution. The posterior distribution is derived analytically from a standard non-informative (Jeffreys) prior. This prior admits a posterior distribution for the reduced form parameters given by

$$\begin{aligned}\Sigma &\sim \mathcal{IW}(\hat{\Sigma}, T - np - 1) \\ \alpha &\sim \mathcal{N}(\hat{\alpha}, \Sigma \otimes Q^{-1}),\end{aligned}$$

where \mathcal{IW} denotes the inverse-Wishart distribution. The vector α is the vectorization of $A = [a \ A_1 \ A_2 \ \dots \ A_{12}]'$, T is the number of observations, n is the number of variables in y_t (4, in this case), and p is the lag order of the VAR (12, in this case). Hats over variables denote the estimated value. The matrix Q is defined to be

$$Q = \begin{bmatrix} \hat{\Gamma}(0) & \hat{\Gamma}(1) & \cdots & \hat{\Gamma}(p-1) \\ \hat{\Gamma}(1) & \hat{\Gamma}(0) & & \vdots \\ \vdots & & \ddots & \vdots \\ \hat{\Gamma}(p-1) & \cdots & \cdots & \hat{\Gamma}(0) \end{bmatrix},$$

where $\hat{\Gamma}(j) = \sum_{t=j+1}^T y_t y_{t-j}'$.

2. The next step is to address uncertainty regarding the identification of the structural model (that is, uncertainty over B_0^{-1}). To do so, for each draw of the reduced form parameters, I draw a large number of rotation matrices B_0^{-1} , following the methodology of Rubio-Ramírez, Waggoner, and Zha (2010). The rotation matrices are constructed as the product of the lower triangular Cholesky factor of Σ and a uniformly random orthogonal matrix P . That is, $B_0^{-1} = \text{Chol}(\Sigma)P$.

Each pairing of a reduced form model with a randomly drawn rotation matrix

corresponds to a different structural model. In the absence of any identifying restrictions, each of the large number of resulting structural models are indistinguishable from the perspective of the data and the model.

3. I then discard all models whose impulse response functions violate the sign restrictions and keep those that satisfy the sign restrictions (the “admissible” models).
4. For each structural model that satisfies the sign restrictions, I construct the probability that that model is the true model following Inoue and Kilian (2013). First, call the structural model parameters θ and let the function $f(\cdot)$ denote a probability density. Let $\text{vec}(\cdot)$ denote the vectorization operator, $\text{vech}(\cdot)$ denote the half-vectorization operator (which vectorizes the diagonal and below-diagonal elements of a matrix), and $\text{veck}(\cdot)$ denote the operator which vectorizes the above-diagonal elements of a matrix. Finally, let $\text{Chol}(\Sigma)$ denote the lower triangular Cholesky factorization of the matrix Σ . Then, the value of the posterior density over structural models evaluated at the model θ can be written as

$$f(\theta) \propto \left(\left| \frac{\partial \text{vec}(\theta)}{\partial [\alpha' \text{vech}(\text{Chol}(\Sigma))' \text{veck}(P)']} \right| \right)^{-1} \left| \frac{\partial \text{vech}(\Sigma)}{\partial \text{vech}(\text{Chol}(\Sigma))} \right| f(\alpha|\Sigma) f(\Sigma).$$

5. Finally, I present the results of the exercise by plotting the impulse responses of the modal (most likely) model with a joint confidence set constructed as the outer envelope of the set of most likely models whose posterior probabilities sum to 90% of the total probability mass. The resulting confidence sets reported in the Section 1.4 are joint confidence sets. Unlike the more commonly used point-wise confidence sets, my confidence sets take account of the dependence of impulse responses across horizons. These confidence sets more effectively control their true coverage.

By characterizing the posterior probability of each structural model, I address two significant shortcomings of standard, point-wise summaries of results. First, in sign-identified models, point-wise measures of central tendency are misleading. Consider the most commonly used point-wise measure of central tendency, the median. The “median response function” is constructed by taking the median of the distribution of all admissible models at each horizon, and stacking the medians into a single vector. This measure of central tendency is very unlikely to correspond to any one structural model. Thus, economists should never expect to actually see such an impulse response. Moreover, even if the point-wise median does correspond to a single structural model, there is no compelling reason to focus on that model. It is simply one of many admissible models.

The second shortcoming I address using posterior probabilities regards the coverage of the confidence intervals. Researchers have long acknowledged that point-wise confidence sets are misleading and may understate the true uncertainty regarding impulse response functions. This is because point-wise sets do not take into account the dependence of impulse responses across horizons. The joint confidence sets shown below do take account of this dependence and so they better control the coverage the confidence interval.

Using sign restrictions allows me to identify informative confidence intervals for the impacts of foreign Treasury purchases on the yield curve without the need to impose economically indefensible restrictions. This does come at some cost: I cannot identify a unique model. As Section 1.4 will show, however, economically reasonable sign restrictions are adequate to characterize the effects of purchases fairly precisely.

1.3 Potential Identifying Restrictions

Before presenting the results of the sign identification exercise, I will discuss the normalization of structural shocks and then enumerate and justify the sign restrictions I use.

I normalize both the sign and the scale of the contemporaneous impact of structural shocks on their own variable. I normalize the structural flows shock to have a \$100 billion impact on the 12-month accumulation of flows in the month of the shock. In spite of the fact that the flows variable is a 12-month accumulation of flows, this normalization means that a structural shock to flows is an increase of purchases within the month by \$100 billion. I normalize shocks to the yield curve factors to have a 25 basis point (bp) impact on their own variable in the month of the shock. Flows and all factors are unrestricted in their response to their own shocks in all subsequent months.

Having discussed the normalization of the structural shocks, I now turn to the three classes of sign restrictions that I consider.

1.3.1 Effect of the Flows Shock on the Level of the Yield Curve

First, I consider restricting that a positive structural shock to flows does not raise the level of the yield curve in the period of the shock. In intuitive terms, I am asserting that if foreign central bankers were to buy \$100 billion of Treasury securities in a single month for reasons unrelated to the yield curve, this would not cause Treasury yields in general to rise in that month. Recall that the level of the yield curve in this paper is the average of the 1-, 5-, and 10- year yields. So, this sign restriction is a restriction on the average of the yields and potentially still allows certain individual yields to rise.

This sign restriction is justifiable on the basis of both economic theory and empirical evidence. Standard asset pricing theory suggests that an increase in foreign demand for Treasuries should reduce yields on Treasuries, if only slightly. With more investors demanding Treasury securities, the prices of Treasury securities must rise to equate the available supply of Treasuries with the increased demand. As prices rise, yields fall. This is referred to as the portfolio balance effect. The portfolio balance effect should, in theory, be small because of the large supply of closely substitutable assets (see Reinhart and Sack (2000)).

More recent theoretical models which capture the “preferred habitat” nature of asset demand would suggest larger impacts of purchases on yields (Vayanos and Vila (2009)).² Such theoretical models assume that there are classes of investors who have a strong preference for particular assets, perhaps due to legal or institutional constraints. For example, many financial institutions are legally required to hold assets which are perceived to have low default risk or whose duration is similar to the institutions’ liabilities. This assumption of preferred habitat demand means that assets are, in fact, less substitutable than they appear. If the assets are less substitutable, then the same logic as in standard asset pricing theory would suggest the impacts of purchases should be larger.

Empirical studies also provide substantial evidence that increases in demand for Treasury securities lower Treasury yields. Bernanke, Reinhart, and Sack (2004), Abe (2007), and Chapter 2 of this dissertation are all event studies which identify significant negative impacts of foreign Treasury purchases on yields. Chapter 2 documents the negative impacts across a range of maturities. Additionally, as the particular purchaser is of only limited importance to the question, the substantial literature on the efficacy of quantitative easing also provides evidence in support of this sign restriction (among others, Gagnon et al. (2010), Krishnamurthy and Vissing-Jorgensen (2011),

²These recent models are based on earlier work, such as in Modigliani and Sutch (1966), and long-held informal beliefs among market participants.

and Wright (2012)).³

In the baseline case (Section 1.4.1), I impose this sign restriction only for the first month, but I do consider strengthening the restriction. In particular, one way in which I consider strengthening the restriction is by extending the restriction beyond the month of the shock (Section 1.4.4). I also consider imposing the stronger but closely related restriction that all three yields individually do not rise with a flows shock (Section 1.4.3). The weakest form of this assumption, imposed in the baseline case, is sufficient to obtain informative results and further strengthening of the restriction has little effect on the results.

1.3.2 Effect of the Flows Shock on the Slope of the Yield Curve

The second class of sign restrictions that I consider are restrictions on the slope of the yield curve. In particular, in the baseline case I impose that the yield curve does not steepen (the slope does not rise) in response to a positive flows shock, in the month of the shock. Given the definition of the slope factor in this paper, this restriction amounts to requiring that the 10-year yield's impulse response is lower than the 1-year yield's in the month of the shock. This restriction by itself does not require either yield's response to be non-positive.

This sign restriction can also be justified on the grounds of economic theory and empirical evidence. To the extent that foreigners tend to buy in the middle and longer sectors of the yield curve, the portfolio balance and preferred habitat effects should be strongest there. Indeed, the substantial foreign accumulation of Treasury securities

³Of course, foreign Treasury purchases and quantitative easing by domestic central banks might influence yields differently. While both should exert direct effects on bond prices by changing outstanding asset supplies, quantitative easing might also influence investor expectations about future policy or about the preferences of policymakers. Swanson (2011) and the discussion that follows the paper offer detail on the channels through which quantitative easing might influence yields. Foreign purchases seem unlikely to exert influence through any such additional channels.

over the past few decades has primarily reflected foreign purchases of Treasury notes and bonds, assets with maturities of greater than one year. Unfortunately, available data does not offer a detailed breakdown of foreign Treasury holdings or purchases by maturity. However, the aforementioned stylized fact supports the sign restriction. Further, the short end of the yield curve, proxied by the 1-year yield in this paper, largely reflects the level of the federal funds rate which is set by the Federal Reserve and adjusted every several weeks. Thus, at least in the short run, the short rate is likely less responsive to purchases than longer, less restricted yields.

Empirical evidence, in the form of event studies regarding recent unconventional monetary policy, also supports this restriction on the slope of the yield curve. For instance, Ehlers (2012) studies the Federal Reserve’s Maturity Extension Program (MEP). In the MEP, the Fed sold \$667 billion of short-maturity Treasuries and used the proceeds to purchase long-maturity Treasuries. Thus, the increase in asset supply at the short end of the yield curve was equal to the fall in asset supply at the long end. Ehlers documents that the impacts of MEP-related announcements on the 5- and 10-year yield were 10 to 20 times larger than the impact on the 1-year yield. Additionally, Krishnamurthy and Vissing-Jorgensen (2011) show more broadly that the impacts of the Fed’s large scale asset purchases (LSAPs) have been much larger on long yields than on short yields.

In addition to the baseline restriction that the slope declines (Section 1.4.1), I consider strengthening the restriction. I consider requiring that both the 5- and 10-year yields are below the 1-year yield (Section 1.4.3) and imposing the restriction over longer horizons (Section 1.4.4). The stronger forms of the restriction have little effect on the results.

1.3.3 Effect of the Flows Shock on Term Premia

A third type of restriction that I consider is on the term premia on 5- and 10-year Treasury bonds. Specifically, a positive flows shock should not raise term premia in the month of the shock.

Decomposing Yields

Before discussing this restriction further, I define the term premium in this model. The yield on a bond with m years remaining to maturity can be divided into two components:

$$i_{m,t} = \frac{1}{m} \sum_{j=0}^{m-1} E_t [i_{1,t+j}] + TP_{m,t}, \quad (1.5)$$

where the first term corresponds to the expectations hypothesis and the second is the m -year term premium. I assume that investors correctly anticipate the impulse response of short rates, so that expected future short rates are proxied by actual future short rates. That is, the impulse response of the first term is just an average of the impulse responses, at the appropriate horizons, of the short rate. The impulse response of the m -year term premium can then be constructed as the difference between the responses of the m -year yield and the corresponding average of expected future short rates.

An additional contribution of this paper is in characterizing the behavior of these two components of yields in response to foreign purchases. Most studies examine the impact of purchases on yields as a whole or on term premia alone. None characterize the impacts on both components, although both expected future short rates and term premia should be expected to respond to purchases.

Economists seem to believe that Treasury purchases (or the outstanding supply of Treasury securities) should only influence term premia. This belief is born out in the

models of Vayanos and Vila (2009) and Hamilton and Wu (2012). Casual discussion among economists and papers such as Beltran et al. (2012) also focus on term premia.

However, purchases might also influence expected future short rates. The Federal Reserve sets the short rate to achieve economic objectives, so if Treasury purchases affect the economy, they should affect (expected) future short rates. As an example, foreign Treasury purchases might broadly lower yields and cause a loosening of credit conditions. The Federal Reserve would then respond either to the loosening of credit or to the ensuing acceleration in the pace of real activity. It would presumably respond by raising short rates and tightening policy. In this example, then, market participants should raise their expectation of future short rates even as term premia fall following foreign Treasury purchases. In this narrative, it is clear that the two components move in opposite directions, meaning that the expected policy tightening dampens the impact of purchases on yields. Indeed, I find evidence of this narrative in Section 1.4. Ignoring the dynamics of both components individually is therefore misleading.

Justifying Restrictions on Term Premia

Restricting the response of term premia following a shock to Treasury purchases is motivated both by standard asset pricing theory and, more powerfully, by preferred habitat models of the term structure. Both theories conclude that purchases should lower yields on the assets being purchased by lowering their term premia (Vayanos and Vila (2009) and Hamilton and Wu (2012)).

Restrictions on term premia are also supported by limited empirical evidence. In particular, Beltran et al. (2012) decompose Treasury yields as described in Equation (1.5) and study the impacts of foreign Treasury purchases on the term premium. They find statistically and economically significant impacts of purchases on the term premium. The impacts on term premia that they find are somewhat smaller than

those found in this paper.

In the baseline case (Section 1.4.1), I impose that a positive structural shock to flows does not raise 5- and 10-year term premia in the month of the shock. This restriction has substantial impacts on the results and I consider relaxing the restriction in Section 1.4.2. Extending the horizon over which the restriction applies has little impact on the results, at least for economically justifiable horizons of less than a year or two (Section 1.4.4).

1.4 Results

I now present the results of the sign identification exercises, grouped by the set of identifying restrictions applied. In each case, I generate 400 million unique structural models before the sign restrictions are applied by pairing each of 20,000 draws of the orthogonal matrix P with each of 20,000 draws of the reduced form parameters from their respective marginal posterior distributions.⁴ Of course, the majority of these structural models are discarded. The distributions used to create the confidence intervals are composed of those models that satisfy the sign restrictions, which never number fewer than 350,000.

The confidence intervals shown are joint confidence sets. That is, the confidence intervals take into account the dependence of models across horizons, unlike conventional point-wise intervals. The confidence intervals are constructed as the outer envelope of the set of most likely models which together represent 90% of the total probability mass in the full empirical distribution of structural models. The modal model is represented by a green line. Within each set of sign restrictions, the modal impulse responses all correspond to the same structural model. See Section 1.2.4 for more on the construction of the confidence sets and the selection of the modal model.

⁴The one exception is in Case 2, where, unfortunately, I must limit the number of models to 100 million. The sign restrictions are sufficiently conservative that many models are admissible and must be saved, posing a problem of inadequate computational memory.

1.4.1 Baseline Case

The baseline set of sign restrictions demonstrates that limited, easily justified restrictions are adequate to identify economically important impacts of foreign purchases. The baseline results also suggest that the Federal Reserve responds to purchases, but only slowly and partially.

In the baseline case, I apply three sign restrictions on the impulse responses to an exogenous \$100 billion foreign purchase of Treasury securities: the impulse responses of the level and slope of the yield curve as well as term premia (on both 5- and 10-year securities) are non-positive in the month of the flows shock.

In brief, it appears that a surprise \$100 billion purchase of Treasuries substantially lowers yields initially, but the effects are offset, with a lag of a few years, by a monetary tightening. The decline in 5- and 10-year yields represents a large decline in term premia coupled with a small rise in expected future short rates. These results suggest that the flows shock causes a loosening of credit conditions, to which the Federal Reserve responds with a monetary tightening. The monetary tightening occurs with a lag and is insufficient to fully offset the impact on term premia for at least the first two years or so after the shock.

Focusing on the factors of the yield curve, the flows shock shifts the level of the yield curve down for a few years, and thereafter raises the level and flattens the slope (Figure 1.1). The response of the level of the yield curve is significantly negative for 25 months following the flows shock. The maximum impact comes 15 months after the surprise purchases, when the level of the yield curve is at least 58 basis points lower than it would otherwise have been. At that point, the modal model shows a decline of 77 basis points while a response of as much as 160 basis points cannot be ruled out. After 3 to 4 years, the level of the yield curve rises significantly, with the short rate rising the most, resulting in a statistically significant flattening of the yield

curve beginning around 3 years after the shock. The confidence interval for the slope of the yield curve 3 to 5 years after the shock ranges between about -35 and -150 basis points and the modal model bottoms at -49 basis points.

Term premia are significantly depressed for several years following the flows shock, but expected future short rates are mostly higher (Figure 1.2). The term premium on the 5-year note is significantly lower for 30 months after the shock and the modal response is still negative after 4 years. The maximum impact on the 5-year term premium comes 13 months after the shock, when the term premium is between 80 and 175 basis points lower. The modal response is lower by 85 basis points. The 10-year term premium is significantly lower for just over 2 years and the modal response is negative for almost 5 years. The maximum impacts on the 10-year term premium occur 13-14 months after the shock, when the confidence interval spans -60 to -177 basis points and the modal response bottoms at -66 basis points.

Yields at all maturities are significantly lower for about 2 years after the shock, with maximum impacts occurring in months 11 through 17 (Figure 1.3). The 1-year yield is lowered by between 53 and 205 basis points, with the modal response lower by 94 basis points. The modal impact on the 5-year yield is 88 basis points, within a confidence interval of 61 to 158. The 10-year yield declines by between 49 and 130 basis points, with a modal decline of 68 basis points.

My results for the impacts on term premia are much larger than found elsewhere. Evidence on the impact of purchases on term premia are limited, but Beltran et al. (2012) estimate an impact on the 5-year term premium of about 50 basis points and an impact on excess returns to holding 5-year notes of 39 to 62 basis points. These impacts are smaller (in absolute value) than mine and lie outside of my confidence interval at the point of maximum impact. A potential explanation for these different results is that I better control for reverse causality.

My results for the impacts on yields as a whole are similar to or a bit larger than

those found elsewhere. Warnock and Warnock (2009) estimate in a time series model at the monthly frequency that a \$100 billion purchase lowers the 10-year yield by about 68 basis points. This estimate coincides with maximum impact on 10-year yield in my modal model, though my confidence intervals are wide enough that much larger impacts are possible. Event studies such as Bernanke, Reinhart, and Sack (2004) and D’Amico and King (2013) tend to find similar results. Rudebusch, Swanson, and Wu (2006) find little or no impact of purchases on yields. Chapter 2 of this dissertation also appears to find impacts about as large as those found here, though some caution is warranted in comparing those results given the different methods employed between the two chapters.⁵

Finally, the results on the decomposition of yields suggest that purchases have meaningful impacts on both term premia and expected future short rates. In spite of this, economists’ discussion of the effects of purchases, either purchases by foreigners or by domestic central banks, often focuses on the impacts on term premia. While I find that term premia are significantly affected, expected future short rates are also affected. Moreover, the impact of foreign purchases on expected future short rates partially offsets the behavior of term premia, meaning yields are affected less than term premia might suggest. So, although short rates may not be free to respond within the month or the quarter, they should not be treated as exogenously fixed. Because monetary policy responds to the state of the economy and credit markets, short rates (and expectations regarding them) are also affected.

⁵Chapter 2 estimates the impact of surprises to expected future Treasury purchases by Chinese officials in intra-daily windows around announcements regarding Chinese policy. The effects on yields are estimated as a function of the innovations in currency forwards. Translating the quantitative results from that approach into the context of cross-border Treasury flows at the monthly frequency is not straightforward. Not only are the time horizons different (as is the case with all event studies), but the measure of unanticipated purchases is also different.

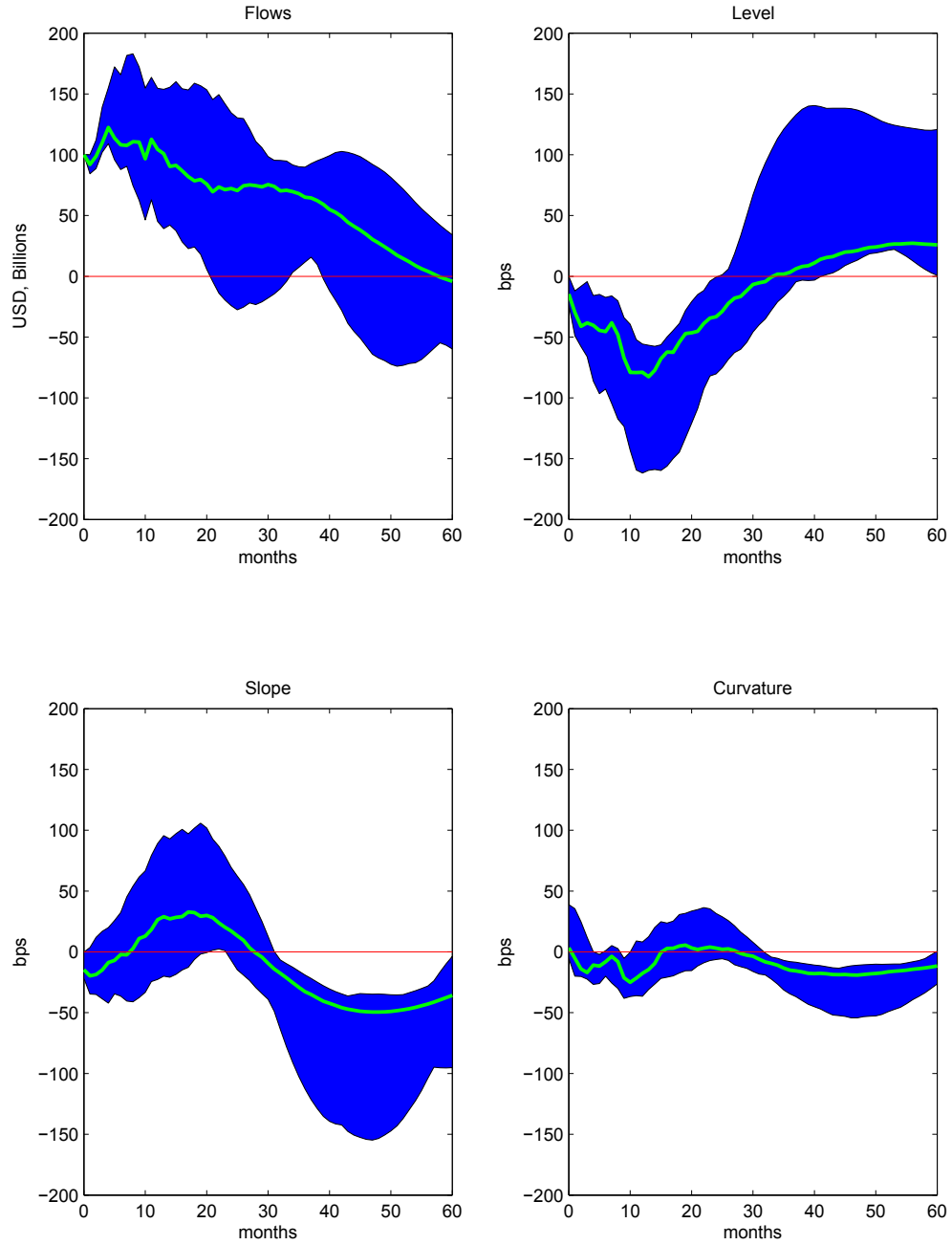


Figure 1.1: Baseline Case, Response of Flows and Yield Curve Factors. The response of all variables in the VAR to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. In the upper left panel (response of foreign Treasury purchases), vertical axis is in billions of USD while the other three panels are in basis points. The horizontal axes are in months following the shock.

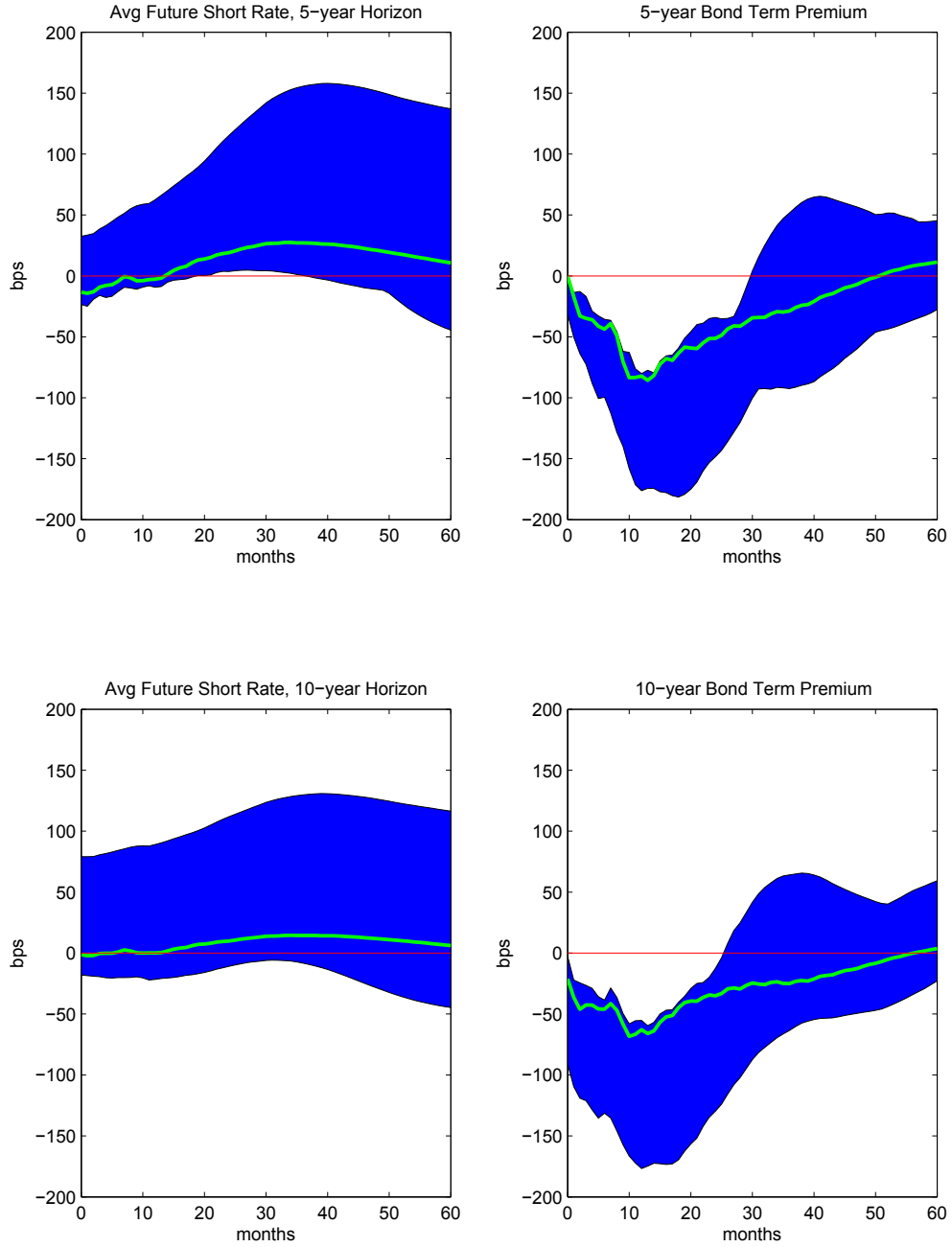


Figure 1.2: Baseline Case, Response of Yield Components. The response of the average of expected future short rates and of term premia to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. The vertical axes are in basis points while the horizontal axes are in months following the shock.

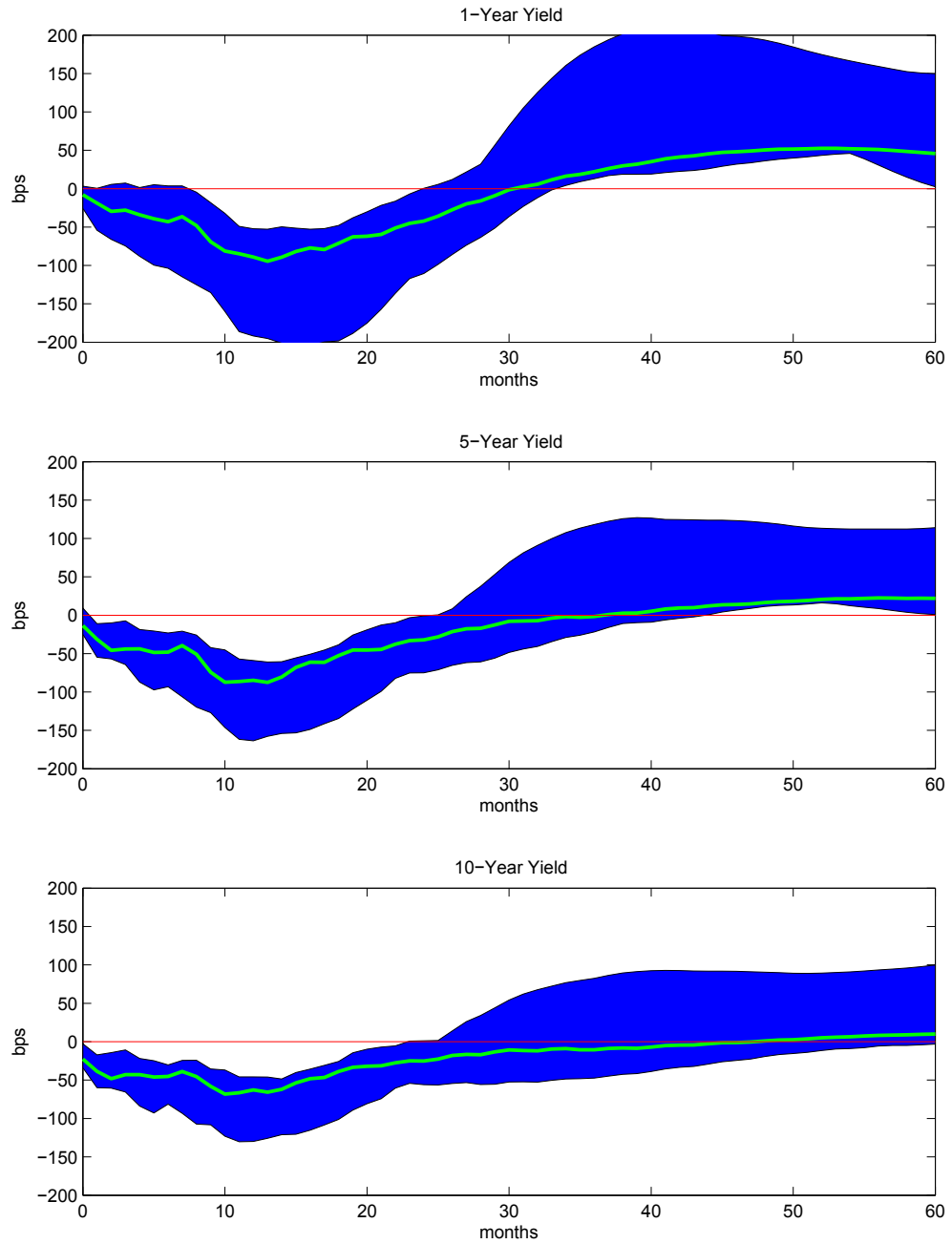


Figure 1.3: Baseline Case, Response of Yields. The response of yields to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. The vertical axes are in basis points while the horizontal axes are in months following the shock.

1.4.2 Case 2: Relaxing the Restriction on Term Premia

Restricting the response of term premia has substantial impacts on the results. In this case, I consider relaxing the restriction on 5- and 10-year term premia and obtain implausible results. I maintain the restrictions on the response of the level and slope of the yield curve in the month of the shock. The only difference relative to the baseline case is that term premia are unrestricted here.

As Figure 1.4 shows, the impacts on term premia and expected future short rates immediately following the shock all have the opposite sign relative to the baseline case. The average of expected future short rates is initially significantly negative here, reflecting the very large and persistent decline in the short rate (Figure 1.5). In the modal model, the response of the expectations hypothesis portion of the 10-year yield is lower by as much as 60 basis points, and the decline is statistically significant for the first 2 and a half years following the shock. At the same time, term premia initially rise. They are significantly higher for the first few months following the shock.

The responses of all yields are larger and more persistent in the absence of the term premium restriction (Figure 1.5). The maximum impacts are realized about 18 months after the shock and the responses differ from zero for about 3 years (1 year longer than in the baseline case). The maximum impact on the 1-year yield is at least 150 basis points. For the 5- and 10-year yields, the maximum impacts are at least 100 and 80 basis points, respectively.

These impulse responses are implausible for a couple reasons, thus supporting the restriction on term premia. First and most important is the fact that term premia initially rise in response to a flows shock in the absence of the sign restriction. That fact is hard to rationalize on the basis of economic theory or existing empirical evidence. Second and less justifiably, the impacts under this identification appear

larger than most economists seem to believe. Viewing the sign identification exercise as an opportunity to directly impose the prior beliefs of the profession in order to achieve identification, I would argue that these results show that the term premia restriction should be imposed.

1.4.3 Case 3: Strengthening the Restrictions on Level and Slope

Strengthening the contemporaneous restrictions on the level and slope of the yield curve has very little effect on the results. In this case, I maintain the restriction on term premia from the baseline case but strengthen the other two restrictions. Strengthening the restriction on the level of the yield curve, I require that all yields individually must not rise in response to a surprise foreign Treasury purchase (within the month of the shock). This is stronger than the baseline restriction on the level of the yield curve, which only restricts the average of yields. Strengthening the restriction on the slope of the yield curve, I require that both the 5- and 10-year yields decline by at least as much as the 1-year yield. This adds the restriction on the 5-year yield relative to the baseline restriction on the slope of the yield curve. All restrictions are imposed only for the month of the flows shock.

Focusing first on the decomposition of yields (Figure 1.6), it is clear that the stronger restrictions only marginally affect the impulse responses. The modal model, which is common to both Figures 1.6 and 1.7, is identical to the modal model in the baseline case. The confidence intervals are somewhat narrower with the stronger restrictions, however. That means that the expectations component of the 10-year yield rises by a statistically significant amount following a positive flows shock. It also means that the responses of both term premia are significantly different from zero for an additional 6 to 8 months. Both term premia are lower for about 3 years following the flows shock in this case. Finally, at maximum impact, the upper end

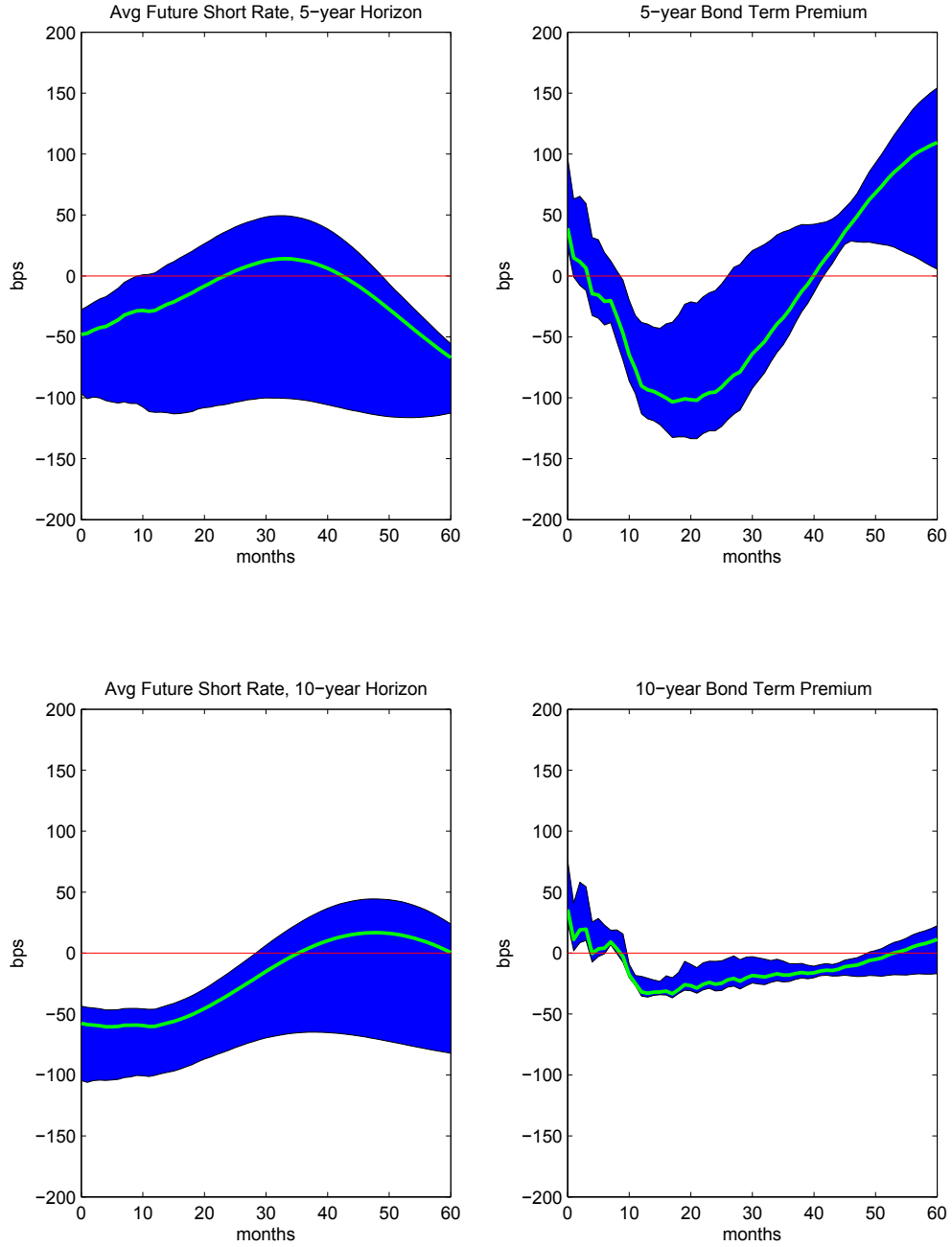


Figure 1.4: Case 2, Response of Yield Components with Relaxed Restrictions on Term Premia. The response of the average of expected future short rates and of term premia to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. The vertical axes are in basis points while the horizontal axes are in months following the shock.

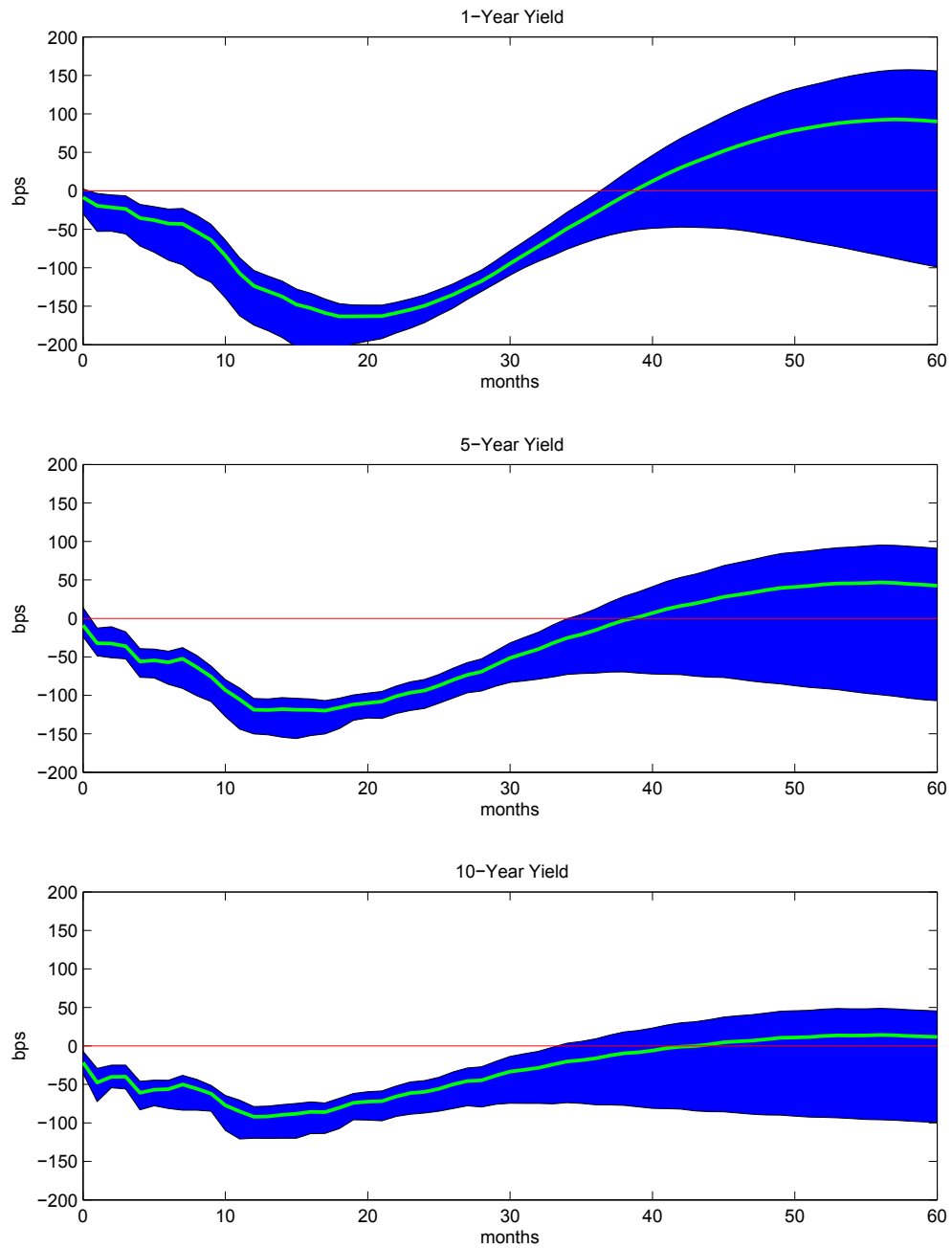


Figure 1.5: Case 2, Response of Yields with Relaxed Restrictions on Term Premia. The response of yields to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. The vertical axes are in basis points while the horizontal axes are in months following the shock.

of the confidence interval for the 10-year term premium is about 3 basis points lower than in the baseline case, at -63 basis points.

The results for yields as a whole are also very similar to those in the baseline case. The confidence intervals are lower by 5 to 10 basis points in the first couple of years after the shock and are generally narrower than in the baseline case. The responses are significantly negative for 2 to 3 months longer. The basic narrative for the impact of a flows shock is unchanged.

1.4.4 Case 4: Extending the Horizon of the Restrictions

In the fourth and final case shown in this paper, it's clear that extending the horizon over which restrictions are applied has little impact on the results. In this case, I restrict that level, slope, and term premia are non-positive for the first 6 months following a flows shock. These are the same restrictions as in the baseline case, but they are applied over a longer horizon. As in case 3, the modal model is the same as the baseline modal model.

The response of the expectations component of the 5-year yield is somewhat more significant and is significant for longer; other confidence intervals are not meaningfully impacted (Figures 1.8 and 1.9). Other than in the upper left panel, the confidence intervals in Figure 1.8 are only about 1 to 3 basis points narrower at any horizon relative to the baseline case. A similarly small difference is evident in the confidence intervals in Figure 1.9.

Obviously, by further extending the horizon over which the sign restrictions hold, I could further affect the impulse responses. However, the restrictions become harder to justify as the horizon grows. It is also worth noting that extending the horizon of the stronger sign restrictions from case 3 has a similarly small impact on the results.

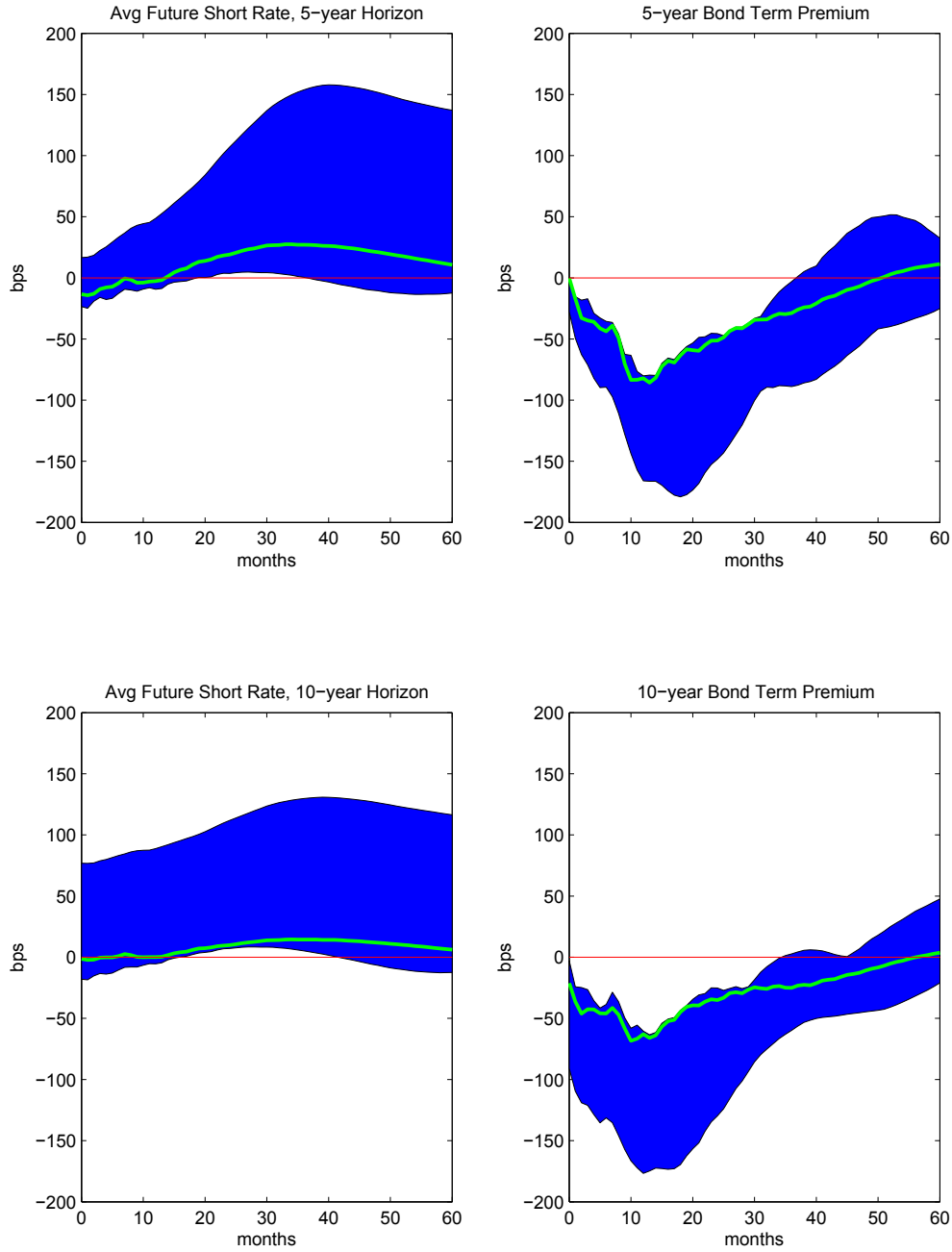


Figure 1.6: Case 3, Response of Yield Components with Stronger Restrictions on Level and Slope. The response of the average of expected future short rates and of term premia to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. The vertical axes are in basis points while the horizontal axes are in months following the shock.

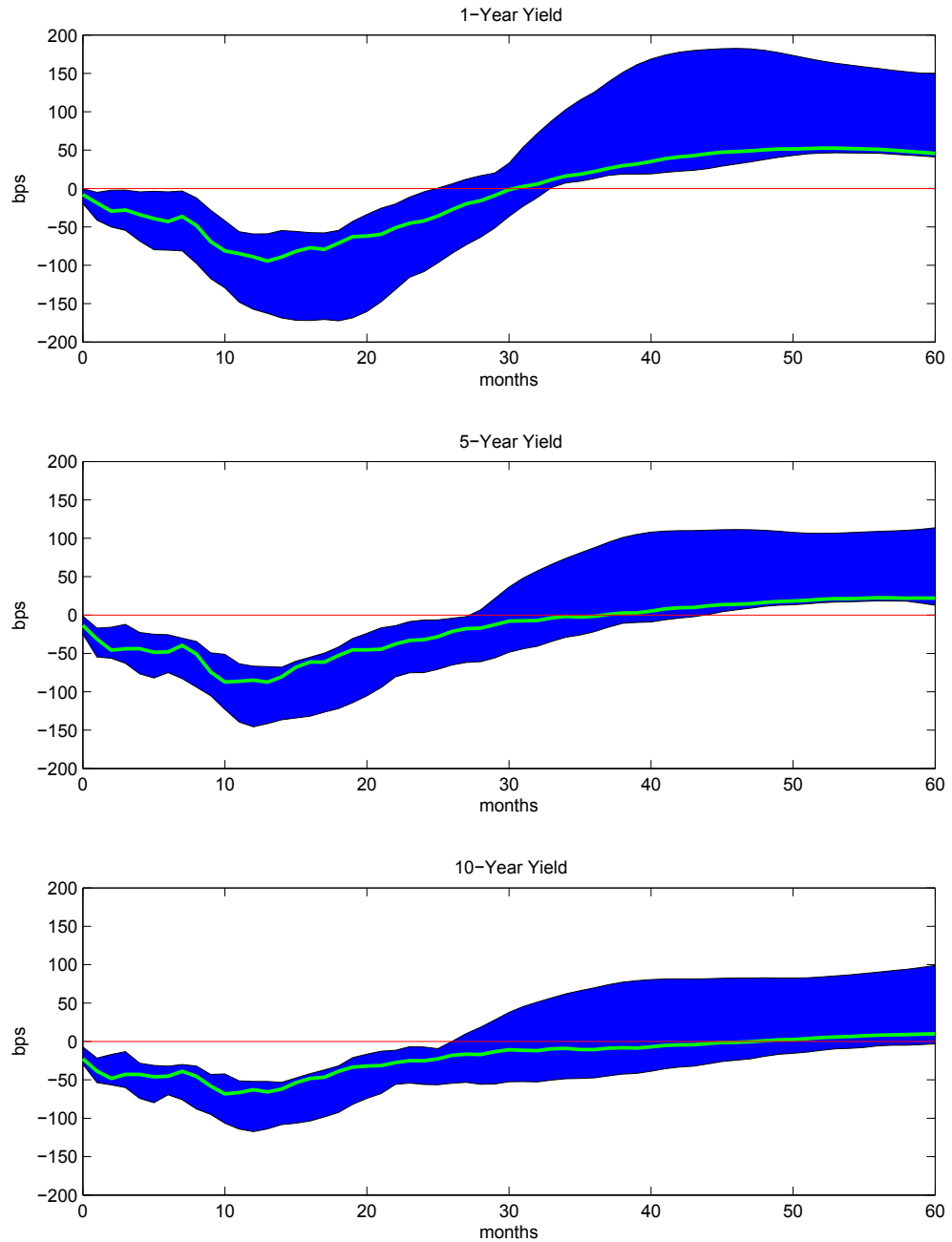


Figure 1.7: Case 3, Response of Yields with Stronger Restrictions on Level and Slope. The response of yields to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. The vertical axes are in basis points while the horizontal axes are in months following the shock.

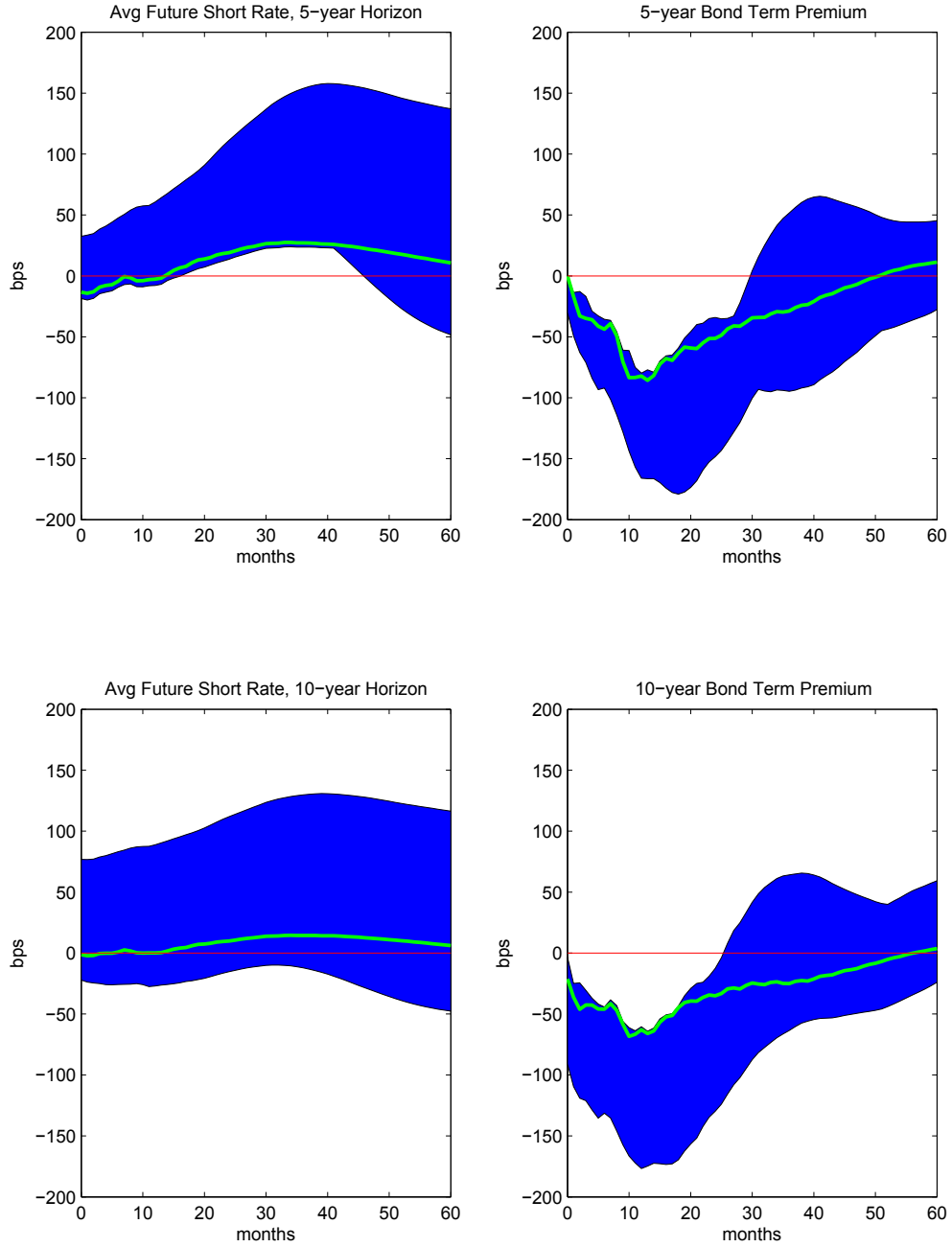


Figure 1.8: Case 4, Response of Yield Components with Extended Horizon of Restrictions. The response of the average of expected future short rates and of term premia to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. The vertical axes are in basis points while the horizontal axes are in months following the shock.

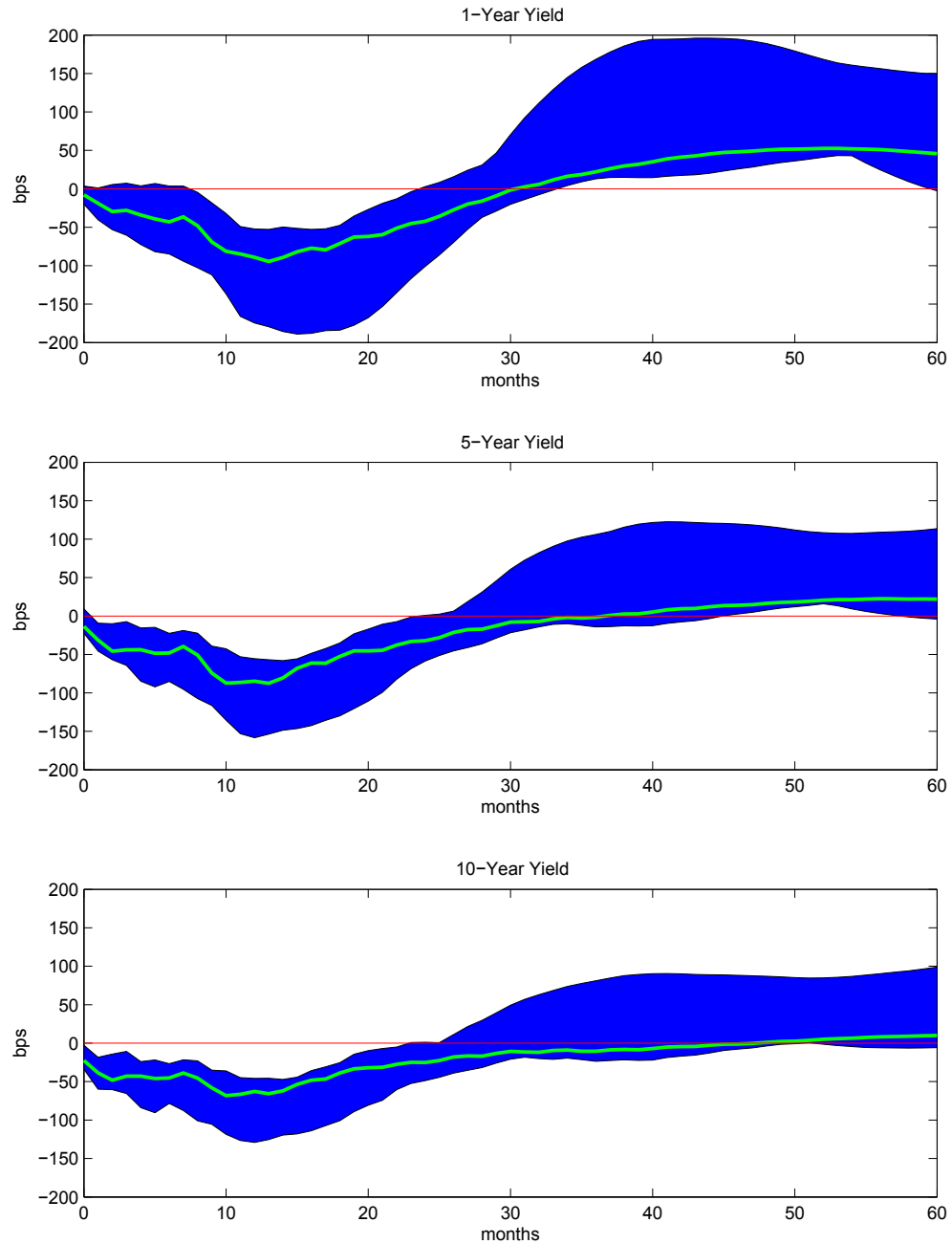


Figure 1.9: Case 4, Response of Yields with Extended Horizon of Restrictions. The response of yields to a positive structural flows shock. The bold green lines are the modal model and the confidence intervals in blue are 90% nominal coverage intervals. The vertical axes are in basis points while the horizontal axes are in months following the shock.

1.5 Conclusion

This paper identifies the effects of foreign Treasury purchases on Treasury yields in the context of a sensible, well-understood identification scheme. While previous papers have investigated the impacts of purchases on yields, their identification schemes are often questionable. Event studies might achieve identification, but by their nature they can only identify the impacts within very narrow windows. These windows are too short to be economically meaningful, and extrapolating their results requires additional assumptions. The instrumental variables approach is promising, but valid and strong instruments for both official and private Treasury flows have yet to be found. So, although the literature has made great progress, the topic is not yet settled.

I take the literature one step further and use a technique not yet applied to this literature, identifying effects that are similar to, or perhaps a bit larger, than those found elsewhere. In my baseline results, I find that an exogenous purchase of \$100 billion of Treasury securities by foreigners in a single month significantly lowers Treasury yields across the term structure for around 2 years following the purchases. The 1- and 5-year yields decline by perhaps 90 to 100 basis points while the ten-year yield declines by about 70 basis points (all within much wider confidence intervals), with the largest impacts coming a year or more after the purchase.

This behavior of Treasury yields reflects the interesting but not previously explored behavior of term premia and expected future short rates in response to purchases. I find that purchases have very large effects of term premia, but that these effects are partially offset by monetary tightening by the Federal Reserve. This monetary tightening slightly raises the expected future path of short rates, thereby dampening the effects of purchases on overall yields.

The results in this paper, beyond directly addressing the impact of foreign Trea-

sury purchases on yields, can shed light on two topics related to recent monetary policy. First and most obviously, these results suggest that the large scale asset purchases recently undertaken by central banks around the world should be effective in lowering long-term interest rates. Domestic central bank purchases of assets might influence the stance of monetary policy in several ways, but it seems clear that if foreign purchases of domestic assets affect domestic interest rates, then so should purchases by the domestic central bank. Second, to the extent that the US housing bubble and subsequent financial crisis were fueled by easy credit, my findings suggest foreign purchases of US assets may have played an important role.

CHAPTER 2

Identifying the Effects of Chinese Treasury Purchases Using High-Frequency Data

2.1 Introduction

In recent years, many economists have concluded that large asset purchases can substantially impact asset prices and yields. This conclusion is supported primarily by empirical research on two episodes in which official purchases of US Treasury securities were quite large: the period in the mid-2000s when Asian central banks were buying Treasuries at an unprecedented rate and the various rounds of large scale asset purchases (LSAPs) undertaken by the Federal Reserve in response to weak US demand following the financial crisis. In the first episode, while foreign officials were buying large quantities of Treasuries, long-term interest rates in the US were unusually low given the state of the macroeconomy (Rudebusch, Swanson, and Wu (2006) and Backus and Wright (2007)). These stylized facts motivated research which suggests that foreign official purchases may have caused the low rates. In the second episode, the Federal Reserve undertook LSAPs with the explicit intention of lowering bond yields and raising asset prices in order to stimulate economic activity. Empirical studies suggest that the LSAPs have been modestly successful in lowering yields.

Understanding the link between official bond purchases and yields is of great significance to policy economists. Some analysts suggest that the period of low long-term interest rates in the mid-2000s helped to inflate asset price bubbles, laying the foun-

dations of the financial crisis. It is telling that the most significant asset price bubble was tied to housing, which is very sensitive to long rates. Clearly, understanding why interest rates were so low is important, as it is central to understanding the roots of the financial crisis. Further, the financial crisis and resulting recession caused short term interest rates to fall to zero in an environment of weak aggregate demand. With short rates at zero, the Federal Reserve has had to find alternative approaches to stimulate aggregate demand, and one of its main innovations has been the advent of LSAPs. So, the effect of large asset purchases, especially official purchases of US Treasury securities, might be part of both the cause and treatment for the financial crisis.

In spite of the importance of and also existing research on the link between official purchases and yields, further empirical research is needed to address two notable issues that remain. First, estimates of the impacts of purchases within and between the two episodes differ greatly. Research on the effects of LSAPs find impacts on yields which are more modest than the estimated impacts of foreign official purchases. Second, and more importantly for this paper, there is a fundamental identification problem which, if left untreated, leads to endogeneity bias.

I address these two concerns by applying a new identification technique to overcome endogeneity and produce reliable estimates of the impacts of foreign official purchases of Treasuries on Treasury yields. Specifically, I construct a new measure of surprise Chinese official Treasury purchases, use high frequency data, and apply the technique of identification by heteroskedasticity. These allow me to obtain unbiased estimates of the effects of Chinese official purchases of Treasuries on Treasury yields and contribute to the existing empirical work on the link between purchases and yields. I find the effects of Chinese purchases to be larger than previous work has indicated, where the difference is plausibly attributed to endogeneity bias. As a benchmark, I find that Chinese Treasury purchases undertaken to maintain the cur-

rency peg may have lowered yields across the yield curve by around 100 basis points in the mid-2000s, with some smaller and substantially larger impacts possible.

As discussed previously, the greatest difficulty in estimating the impacts of foreign official purchases on yields is that such purchases are endogenous. Not only might purchases affect yields, but yields might effect purchases. Indeed, this chapter and the previous suggest that causality runs in both directions. First, in the simplest intuitive terms, purchases can affect yields because purchases represent an increase in demand for the securities, causing their prices to rise and yields to fall. Second, yields can affect foreign official purchases because many foreign central banks maintain exchange rate targets. Because yields drive movements in exchange rates which must be offset by foreign exchange interventions, which most often take the form of Treasury purchases, yields indirectly drive purchases. Thus, causality runs in both directions between purchases and yields. This simultaneity leads to the fundamental identification problem.

Failing to take address this simultaneity leads to biased estimates of the impact of purchases on yields, and I present evidence that this bias is toward zero. Specifically, I find that a positive shock to Treasury yields causes a decline in foreign official purchases. This would cause studies failing to fully control for endogeneity to find smaller impacts of purchases on yields, potentially explaining why the estimates in this paper (and Chapter 1) are generally larger than those in the existing literature. Moreover, it is not surprising that an increase in yields would cause a decline in foreign official purchases. For example, suppose that better-than-expected news about the US economy arrives or that the Federal Reserve increases the fed funds target by more than expected. Conventional theory says that these events should tend to raise US interest rates and cause the dollar to strengthen. The stronger dollar, in turn, decreases the pressure on foreign central banks to buy dollars to keep their currencies undervalued.

The literature on the effects of foreign purchases of Treasuries has gradually begun addressing the endogeneity problem. Most of the early research in this literature assumed the impacts of yield changes on purchases was sufficiently small that the simultaneity could be ignored and one could simply regress yields on purchases (Rudebusch, Swanson, and Wu (2006) and Warnock and Warnock (2009)). Subsequent research has applied three standard identification schemes to address the endogeneity. Beltran, Kretchmer, Marquez, and Thomas (2013) apply instrumental variables to overcome endogeneity in a low-frequency VAR setting, though strong and valid instruments are difficult to find.¹ Chapter 1 of this dissertation applies the technique of sign identification in a low-frequency VAR, though such an identification scheme cannot identify a unique set of model parameters. Lastly, relatively early research by Bernanke, Reinhart, and Sack (2004) used an event study method at the daily frequency. While event study techniques can in principle overcome endogeneity, this paper finds that event study estimates are potentially still subject to endogeneity.

To contribute a new estimate of the impacts of purchases on yields, I combine intradaily data and the technique of identification by heteroskedasticity (IDH) (Rigobon (2003)). By focusing on very narrow time windows, I can reduce the endogeneity bias in the same way that an event study (ES) would, although I find that a simple ES model still suffers from significant endogeneity bias in this case. Adding IDH, discussed below, addresses this remaining endogeneity by exploiting known changes in the variance of structural policy shocks across the sample of data.

To implement IDH, I will need three items: a high-frequency measure of changes in Treasury yields, a high-frequency measure of surprise foreign official purchases of Treasuries, and a subsample of the data in which the shock to surprise purchases is highly variable. I must have these three items over the entire sample period, which runs from 2005 through 2014. Measuring changes in Treasury yields is straightfor-

¹Sierra (2010) also employs IV using a similar set of instruments.

ward: I use the rates implied by soonest-to-expire (“front”) 5- and 10-year Treasury note futures and 30-year Treasury bond futures. Futures contract prices are available intraday and overnight, making them a natural choice for my purposes. The measure of surprise foreign official purchases, however, is more complicated.

Another contribution of this paper, then, is in creating a new measure of surprise foreign official purchases based on currency forward contracts. The difficulty arises because, while I would like to have a measure of the dollar value of the surprise component of foreign official Treasury purchases, no such measure is available. The ideal surprise variable would be constructed as the difference between expected and announced Treasury purchases by Chinese officials. However, there is no data which could be used to directly measure market expectations of Chinese official Treasury purchases. Further, Chinese officials do not announce their schedule of Treasury purchases, either before or after the purchases are made. I also need a high-frequency measure of this hard-to-measure surprise. To construct a proxy measure of surprise purchases, I focus on China and use changes in prices on US dollar (USD)/Renminbi (RMB) currency forward contracts. The change in forward contract prices can be thought of as a measure of the exchange rate surprise. Surprises in the level of pegged exchange rates translate directly into surprises in expected official purchases of Treasuries, since such purchases are made to maintain the peg at the chosen level.

Finally, I must identify two subsamples in the data, one in which the variance of the shock to exchange rate expectations is higher and one in which it is lower. IDH exploits this heteroskedasticity to identify the model and overcome endogeneity. To identify a subsample in which shocks to exchange rate expectations (and thus Chinese official purchases) are highly variable, I identify a set of 30 days (the “event set”) on which Chinese officials made apparently surprising statements regarding their foreign exchange policy. On these announcement days, we should expect the shock to exchange rate expectations to be larger than on other, non-announcement days.

Section 2.2 discusses the structure of the model and explains IDH. With the context of the model and IDH in hand, Section 2.3 discusses the event set, in which Chinese officials made surprising announcements, and how the set was chosen. Then, Section 2.4 describes the data and the financial assets that underly it; Section 2.5 presents the results and compares them both with the existing literature and with simple ES estimates; and Section 2.6 concludes.

2.2 Model Structure and Identification

The purpose of this section is to describe the model and identification technique (IDH) that I will use to obtain unbiased estimates of the impact of Chinese official purchases. This section will provide the necessary context for the discussion of the event set and data construction which follow.

Consider the model given by

$$\Delta e_t = \beta \Delta y_t + \varepsilon_t \tag{2.1}$$

$$\Delta y_t = \alpha \Delta e_t + \eta_t. \tag{2.2}$$

Here, Δy_t is the change in Treasury yields (for 5-, 10-, or 30-year Treasuries) and Δe_t is the surprise to exchange rate expectations at a particular horizon (1 week, 3 months, or 12 months). More detail on the precise construction of these variables will be given in Section 2.4. Recall that exchange rate surprises are a proxy measure of surprise purchases of Treasury securities by Chinese official institutions. This model captures the two directions of causality discussed above: purchases drive yields and yields drive purchases. Note that this model explicitly ignores other variables which might drive yields and exchange rates (or Treasury purchases). This exclusion is justifiable because I will be measuring yield and exchange rate changes over very narrow intraday windows which exclude other sources of variation (or at least systematic sources). The

exclusion is also necessitated by the fact that other relevant variables are generally not measured at such high frequency.

This model presents the standard simultaneity problem. As the model is stated, the two equations cannot be estimated by OLS because the resulting estimates would be biased. This arises because the simultaneous equations imply that the regressor in each equation is correlated with the error term.

Now, consider the model in matrix form in order to view the identification problem from another perspective. The model can be rewritten as

$$\begin{bmatrix} 1 & -\beta \\ -\alpha & 1 \end{bmatrix} \begin{bmatrix} \Delta e_t \\ \Delta y_t \end{bmatrix} = \begin{bmatrix} \varepsilon_t \\ \eta_t \end{bmatrix},$$

or

$$\begin{bmatrix} \Delta e_t \\ \Delta y_t \end{bmatrix} = \left(\frac{1}{1 - \alpha\beta} \right) \begin{bmatrix} 1 & \beta \\ \alpha & 1 \end{bmatrix} \begin{bmatrix} \varepsilon_t \\ \eta_t \end{bmatrix}. \quad (2.3)$$

Taking the variance of both sides of this equation, we obtain

$$\begin{bmatrix} V_e & V_{ye} \\ V_{ye} & V_y \end{bmatrix} = \left(\frac{1}{1 - \alpha\beta} \right)^2 \begin{bmatrix} 1 & \beta \\ \alpha & 1 \end{bmatrix} \begin{bmatrix} \sigma_\varepsilon^2 & 0 \\ 0 & \sigma_\eta^2 \end{bmatrix} \begin{bmatrix} 1 & \beta \\ \alpha & 1 \end{bmatrix}'.$$

Matrix algebra yields

$$\begin{bmatrix} V_y & V_{ye} \\ V_{ye} & V_e \end{bmatrix} = \left(\frac{1}{1 - \alpha\beta} \right)^2 \begin{bmatrix} \sigma_\varepsilon^2 + \beta^2 \sigma_\eta^2 & \alpha \sigma_\varepsilon^2 + \beta \sigma_\eta^2 \\ \alpha \sigma_\varepsilon^2 + \beta \sigma_\eta^2 & \alpha^2 \sigma_\varepsilon^2 + \sigma_\eta^2 \end{bmatrix}. \quad (2.4)$$

Given that the left hand side is observable, this yields a set of three equations (one each for V_y , V_{ye} , and V_e) in four unknowns: α , β , σ_ε^2 , and σ_η^2 . Clearly, there are not enough equations. This is the identification problem caused by simultaneity/endogeneity

from another perspective.

Considering the identification problem from these two perspectives simultaneously provides the foundation for understanding the identification schemes in both the ES methodology and in IDH. I will discuss the identification technique in an ES first, both because IDH can be viewed as a relaxation of the identifying assumptions of event studies and because the ES approach provides a useful introduction to the structure of IDH. In any case, I will discuss the shortcomings of the ES estimators (relative to the IDH estimators) in Section 2.5.3, so a review of the ES model is warranted. After discussing the ES identification scheme, I will discuss IDH.

2.2.1 Identification in the Event Study Model

In the event study model, the parameter of interest is α , which is the effect of exchange rate or Treasury purchase surprises on yields. As discussed above, simultaneity gives rise to endogeneity bias, so the estimate of α obtained by simply applying OLS to Equation (2.2) will in general be biased. In particular, the probability limit of the OLS estimate of α will be given by

$$\text{plim } \hat{\alpha} = \alpha + (1 - \alpha\beta) \frac{\beta\sigma_{\eta}^2}{\sigma_{\varepsilon}^2 + \beta^2\sigma_{\eta}^2}$$

The ES identification scheme is to apply the model to changes in yields and exchange rates only over very short windows around events in which the structural shock to exchange rates (or Treasury purchases) is believed to be large. The events are selected based on narrative analysis or knowledge of institutional detail and the windows over which changes are measured are chosen to be small enough that, presumably, the only thing driving changes in both variables of interest is the structural exchange rate shock. By narrowing the sample of data to times of such events, the identifying assumption is that the variance of ε , σ_{ε}^2 , is much larger than the variance

of the η , thus minimizing or eliminating the endogeneity bias. In the limit, as σ_η^2 goes to zero (or the ratio of the variances becomes infinitely large), the bias vanishes. From the perspective of the model in matrix form (Equation (2.4)), the identifying assumption is that $\sigma_\eta^2 = 0$, reducing the number of unknowns to three and leaving the system of equations exactly identified. In principle, the shorter the window of time around the event, the more likely this assumption is to be true.²

In some cases, including some in this paper, this identifying assumption appears to be too strong for practicably short windows around events. Rigobon and Sack (2004) point out that for some event studies using windows as small as one day, the assumption appears to be violated sufficiently to generate statistically significant bias. I also find, in the context of the model above, that significant bias remains even with windows as short as one hour around announcements. In particular, for some measures of exchange rate surprises, my ES estimates appear to be biased and inconsistent.

Because my coefficient of interest apparently may remain biased due to the violation of the identifying assumption, weaker identifying assumptions are needed. Fortunately, IDH provides such a set of assumptions.

2.2.2 Identification by Heteroskedasticity

Identification by heteroskedasticity (Rigobon (2003) and Rigobon and Sack (2003, 2004, 2005)) allows the ES identifying assumption on structural error variances to be relaxed. Whereas the identifying assumption above was that σ_ϵ^2 must be infinitely large relative to σ_η^2 around events, the assumption of IDH is simply that the relative difference between the two on event days must be larger than it is on all other days. Considering a larger sample of days composed of both event days and non-event days, assuming the ratio of shock variances changes across the two subsamples, and assum-

²Of course, the window must remain wide enough to allow for market participants to learn of the event, digest the information, and re-price the financial assets underlying the data.

ing that α and β are constant across both subsamples is sufficient to exactly identify the model. From the perspective of the model in matrix form, these assumptions jointly imply that there are six unknowns and six equations. The unknowns are α , β , $\sigma_{\varepsilon,a}^2$, $\sigma_{\nu,a}^2$, $\sigma_{\varepsilon,na}^2$, and $\sigma_{\nu,na}^2$, where subscript a denotes variables on announcement or event days and na denotes non-announcement days. The six equations correspond to the Equation (2.4), with three equations from announcement days and three from non-announcement days. While the ES methodology solves the identification problem by assuming a zero restriction to eliminate an unknown, IDH exploits assumed heteroskedasticity in the structural shocks to add equations.

The validity of the assumption regarding heteroskedasticity is crucial to the identification scheme and relies upon the division of the full sample of all days into the two subsamples. In particular, the set of events must be chosen carefully. My selection of these events is discussed in the next section.

2.3 Selection and Discussion of the Event Set

In this section, I discuss the set of events and how they were chosen. The events are all announcements made by Chinese officials regarding the future path of Chinese exchange rate policy or official Treasury purchases. An example of such an event would be the announcement in July 2005 that the PBOC was revaluing their currency by 2.1% and dropping a fixed peg in favor a managed float. Another example was the reassurances by the governor of the PBOC that the PBOC intended to keep buying Treasuries in spite of market participants' fears that China was already diversifying its foreign exchange reserves away from Treasuries and US dollars. Intuitively, these events are plausibly times when the structural shock to exchange rates is relatively volatile (relative to other days) and thus the heteroskedasticity assumption is valid. However, choosing the event set to obtain clean identification requires care and I

discuss the details in this section. Broadly, I chose the event set with two objectives in mind: to ensure that the heteroskedasticity assumption is valid and to ensure that my results do not suffer from sample selection bias.

In order for the heteroskedasticity assumption to be valid, there are three conditions for the events: they must be significant, exogenous, and specific announcements. The events are significant in the sense that they are announcements by officials in positions of power (such as the central bank governor and premier) whose views of Chinese policy are important and the announcements are noteworthy enough to be mentioned in the popular press. The events must be significant in order for the structural shock to exhibit higher variance around announcements. If one included announcements by low-level officials which were not of interest to market participants, then the announcements would not result in shocks to asset prices, and exchange rates in particular. Including such insignificant announcements in the event set would thus invalidate the heteroskedasticity assumption. However, simply verifying that exchange rates and Treasury yields moved significantly in response to the announcements could give rise to sample selection bias. Thus, I employed an objective rule of searching the PBOC's website and the print edition of the *Wall Street Journal* to determine significance, and did not use the observed behavior of asset prices in selecting events.

The events are exogenous in that they are announcements about Chinese policy intentions by government officials which do not appear to be motivated by anticipated or actual changes in US Treasury yields (or anything correlated with yields) in the event window. This ensures that the moves in yields observed around announcements represent true structural policy (or exchange rate or Treasury purchase) shocks, and not an endogenous response of exchange rates to yield changes. For example, if I suspected that the PBOC announced a policy change at 7am on Monday anticipating a shock to Treasury yields expected to arrive at 7:15am, I would exclude this announcement because it does not appear exogenous. In practice, I did not identify

any such endogenous events, but the stark example illustrates the requirement of exogeneity. I also exclude speculation about future Chinese policy by anyone other than officials who actually decide such policy, as these discussions do not represent sudden, exogenous changes in publicly available information.³

Finally, the event set includes only announcements which are specific. That is, I use only announcements which contain clear information about future Chinese exchange rate policy or Treasury purchases and which contain little else. The event set therefore excludes items such as releases of data about the state of the Chinese economy. These announcements should and do have effects on the expected future path of Chinese foreign exchange policy, but the announcements contain a great deal of other information which might plausibly affect exchange rate policy and US Treasury yields. That is, such events do not represent structural policy shocks.

Having estimated the model, it is possible to verify that the heteroskedasticity assumption is valid, and it is valid for my set of events. The above three conditions are sufficient and thus the ratio $\frac{\sigma_{\varepsilon}^2}{\sigma_{\eta}^2}$ is larger on announcement days than non-announcement days.

With the second broad objective in mind, I used an objective rule in generating the event set in order to avoid sample selection bias. I chose the events by searching the website of the PBOC for relevant announcements and also performed a keyword search of printed *Wall Street Journal* articles referencing news shocks regarding Chinese exchange rate policy. Of the set of events identified by these searches, I include all events for which I was able to obtain a measure of the announcement time and which can be argued to satisfy the three conditions for heteroskedasticity.⁴

³The one exception to this rule was an article in the *New York Times* which reported that an unnamed, high-level source at the PBOC told the *New York Times* that the PBOC was going to announce an end to the nearly two-year-old currency peg, initiated in response to the financial crisis, and announce a new round of currency appreciation. While this report turned out to be untrue, market participants interpreted the report as coming from the PBOC, so I left it in the event set.

⁴Of course, some judgment is required here, particularly in assessing the significance of announcements posted to the PBOC's website (in contrast, I assume anything worthy of publication in the *Wall Street Journal* satisfies the significance condition). However, there are very few events for

Because I will use intraday windows around announcements, I must have information regarding the precise time of day at which each announcement reached the market. For events identified from the PBOC website, this time is provided by the timestamp on the press release. For events identified from the *Wall Street Journal*, this time is taken to be the timestamp on the first Bloomberg article which clearly mentions the announcement. It appears that the delay in publishing news events on Bloomberg is typically quite short, on the order of 15 minutes or less. So, this method yields a reasonable approximation to the announcement time. There were twelve events identified by searching the *Wall Street Journal* for which I could not obtain a precise announcement time; these events are excluded from the set of thirty. This selection method ensures that my sample does not generate any sample selection biases. For example, I did not restrict the sample to announcements which were well-behaved in the sense of yields and exchange rate expectations moving in the expected manner. The set of events includes all events identified by the above search criteria for which I was able to obtain precise announcement times.

Finally, I restricted the search for events to the period starting when Chinese monetary authorities first announced that they were ending their fixed exchange rate regime on July 21, 2005 and ending on April 30, 2014. I exclude earlier days because Chinese officials had not previously announced any intention to set the exchange rate at any level other than the current level of the peg. Thus, there were no exogenous and specific announcements regarding the future path of policy. Any news regarding the path must have come from, for example, economic data releases in China or speculation by market participants, which should be excluded based on the discussion above. The end date of April 30, 2014 is based on the availability of Treasury futures data.

Table 2.1, in the next section, lists the date, time, and source of the announcement which judgment is necessary.

ments, along with some summary of the data. Brief descriptions of the events are provided in Appendix A.

2.4 Construction of the Variables

In order to implement the set of six equations based on Equation (2.4) and to solve for the six unknown model parameters, I must construct the two observed data series: Δy_t and Δe_t . There will be one observation for each of the two series on every US business day from January 1, 2005 through April 30, 2014.

The Treasury yield change series Δy_t is based on yield changes over a one hour period on each business day. For days on which there is an announcement included in the event set, that one hour period is centered around the time of the announcement. For non-announcement days, the center of the window is chosen randomly. I choose one-hour windows both to ensure that the announcements in my event set are in fact covered by the window and to allow market participants time to digest the news in the announcements. Recall that I time many of the events by the timestamp on Bloomberg articles, which are published with a delay of a few minutes, leading to slight imprecision with event timing. Windows as small as 30 minutes do not substantially change the results but do risk leaving some announcements outside the windows. Larger windows appear undesirable, as they only serve to add noise to the measured impacts of announcements.

The yields used to compute yield changes are taken from the soonest-to-expire (“front”) Treasury note and bond futures. I use data from the futures market, rather than the spot market, because Treasury futures are traded on an electronic exchange at the Chicago Board of Trade (now the Chicago Mercantile Exchange). As a result, I can obtain prices for standardized contracts at high frequency, even overnight. Obtaining overnight data is particularly important, as many of the announcements

occur during business hours in China, which is overnight in the US. Over the counter spot markets are extraordinarily thinly traded overnight, meaning there would be very little pricing data from the spot market precisely when I need such data.

The particular Treasury futures contracts I use are what are referred to as the 5- and 10-year Treasury note futures and 30-year Treasury bond futures, but each contract typically corresponds to a security shorter than its name would suggest. This arises because the settlement practices of the futures contracts allow for delivery of a variety of securities with a range of maturities and coupon rates. To ensure that the short investor does not always deliver the lowest-priced eligible security, the settlement practices employ a conversion factor invoicing system to standardize the value of the eligible securities. If the invoicing system worked perfectly, the short investor would be indifferent among all eligible securities. In practice, the system is imperfect, and certain securities tend to emerge as the “cheapest-to-deliver.” Typically, the cheapest-to-deliver security on any contract is the eligible security with the shortest duration. Thus, the maturity of the delivered security is typically on the lower end of the eligible maturity range, meaning that the 5-year futures contract corresponds more closely to something like a 4.5-year note, the 10-year futures contract to a 7-year note, and the 30-year futures contract to a bond with around 15 to 17 years remaining to maturity. Having noted that the futures naming convention may be slightly misleading, I will ignore this confusion henceforth. I will use the three measures of Treasury yields separately, implementing independent models for each.

For each of the three Treasury futures contracts, I calculate the yield change from the security price in the front futures contract according to the duration-based approximation given by

$$\Delta y_t = -\frac{\log(P_{\text{end of window}}) - \log(P_{\text{beginning of window}})}{\delta},$$

where δ is the modified duration of the security which was cheapest-to-deliver into the September 2014 contract as of mid-June 2014. While using the duration of the cheapest-to-deliver security on any given contract and day over the entire sample is desirable, the added complication has minimal impact on the results. I express the yield changes in basis points unless noted otherwise.

Now consider the second data series I need, Δe_t . As discussed in Section 2.1, I employ a novel proxy for surprise foreign official Treasury purchases using exchange rate surprises. I construct the exchange rate surprise as the one-day change in US Dollar (USD)/Renminbi (RMB) forward currency rates. Under the plausible assumption that the value of USD/RMB exchange rate peg is proportional to expected Chinese official Treasury purchases, I have constructed a proxy for surprises to expected Treasury purchases.

Such a proportional relationship might hold between the two variables in a model with a stable equilibrium exchange rate; in which Chinese authorities held only Treasury securities as foreign exchange reserves; and in which the dollar value of foreign exchange interventions exhibited a stable relationship with the deviation of the exchange rate from equilibrium. In such a model, if Chinese authorities wanted to depreciate their currency by $X\%$ relative to the equilibrium exchange rate, they would purchase $\$Y$ of Treasury securities. In that case, there is a clear proportionality between the pegged level of the exchange rate and official Treasury purchases.

Assuming such a model invites at least two criticisms, but the new surprise variable is still reasonable. First, the equilibrium exchange rate surely varies through time, although it is never actually observed in the case of China because Chinese authorities are apparently pegging their currency at a level other than equilibrium. However, the expected equilibrium exchange rate likely does not change significantly over a single day around announcements regarding foreign exchange interventions, so the first assumption is reasonable in this context. Second, Treasury securities are

not the only asset Chinese authorities hold as foreign exchange reserves. They do, however, represent the majority of Chinese foreign exchange reserves. The actual figures are kept secret, but estimates suggest Treasury securities and close dollar-denominated substitutes (such as Agency and highly-rated corporate debt) represent around two-thirds of total Chinese foreign exchange reserves and almost all of the dollar-denominated assets held by Chinese authorities (Setser and Pandey (2009)). Given that, if Chinese authorities announce a change in their future dollar purchases or in the path of the USD/RMB exchange rate, we should expect this to entail systematic changes in future purchases of Treasury securities (or close substitutes). Whether Chinese authorities change their purchases of only Treasuries or of both Treasuries and Agencies is of little importance, given the close substitutability of these assets (for evidence of this substitutability, see Krishnamurthy and Vissing-Jorgensen (2011)). Thus, the new surprise variable constructed in this paper is a reasonable, if not ideal, measure of the surprise contained in Chinese policy announcements.

Summarizing, I use the exchange rates on the last 1-week, 3-month, and 12-month non-deliverable forward (NDF) contracts⁵ traded on each day that US markets are open to generate the surprise variable. The variable is constructed as the log-change between the market close before the announcement to the market close after the announcement and expressed in basis points:

$$\log(P_{\text{first market close after event}}) - \log(P_{\text{last market close before event}}).$$

This means that I construct three different measures of the surprise, one corresponding to each contract (or expectation) horizon. Finally, the use of market-close data means that the smallest event window available in the NDF data is one day. Although it would obviously be desirable to use higher frequency NDF data, none is available.

⁵The contracts are traded at the Chicago Mercantile Exchange, where, being outside of mainland China, Chinese currency is non-deliverable due to capital account restrictions. Thus, the contracts are net-settled in US dollars. Hence the name “non-deliverable forward” (NDF).

Currency prices are quoted as the RMB price of a USD, so a rise in the exchange rate is a weakening of the RMB and strengthening of the USD. Using the three measures of the surprise (corresponding to the three NDF horizons) means that there are three independent models for each of the three independent measures of yields, discussed above. As a result, I estimate nine independent models corresponding to all pairings of the three yields and three surprises.

Table 2.1 presents the set of thirty events, discussed in the above section, and presents the change in the Treasury yields and exchange rates at varying horizons. The “Time” column refers to the time in Chicago, rounded to the nearest 5 minute interval, and the “Source” column names the agency which made the announcement (or the agency at which the official who spoke works). “Ant. Δi ” gives the direction in which conventional theory and common sense would suggest Treasury interest rates should move in response to the news. The next three columns give the change in the interest rate implied by Treasury futures prices for 5-, 10-, and 30-year Treasuries. The last three columns give the change currency forward rates at the 1-week, 3-month, and 12-month horizon, expressed in basis points (so that an entry of “100” corresponds to a 1% change, say from 7 to 7.07).

Focusing first on changes in Treasury yields, this table seems to indicate that when the PBOC says something concrete about its peg or its purchases of dollar-assets, Treasury prices respond in the predicted direction, although only by very small amounts (quite possibly owing to the fact the news events contain small amounts of news, particularly relative to the size of the Treasury market). Not surprisingly, markets do not seem to react as strongly when someone other than the PBOC speaks.

Focusing now on the joint behavior of Treasury yields and currency futures, it appears that an increase in expected future Chinese official purchases of Treasuries decreases Treasury yields (and vice versa). Because the exchange rate is expressed as the price of one USD in RMB, an appreciation of the RMB is a decrease in the

exchange rate. This means that if news arrives suggesting the PBOC will allow the RMB to appreciate by more than the market previously expected, currency forward rates should decline. At the same time, market participants should expect the PBOC to buy fewer Treasury bonds going forward, meaning the price of Treasury bonds (in spot or futures markets) should decline and Treasury yields should rise. That is, if the announcements are the driving factor in these financial markets during the event windows, we should expect a negative correlation between Treasury yield and currency forward changes. Indeed, yields and exchange rates are negatively correlated over the set of thirty events.

To summarize before moving on to the results, I use the two reduced-form variance-covariance matrices of the two data series discussed in this section (one each from the two subsamples of the data) to generate six equations according to Equation (2.4) and solve those equations to obtain point estimates of the model parameters. This exercise is repeated for nine different models composed of each possible pairing of the three Treasury futures and three currency forward contracts. The results of this exercise are discussed next.

Date	Time	Source	Ant. Δi	Δi (bp)			ΔNDF (bp)		
				5yr	10yr	30yr	1W	3M	12M
7/21/05	0600	PBOC	\uparrow	4.7	5.2	4.2	-212.6	-225.1	-37.2
7/26/05	0330	PBOC	\downarrow	-.7	-.2	-.5	1.0	12.5	12.9
9/9/05	1305	PBOC	\uparrow	1.3	.7	.5	2.8	5.6	12.7
11/25/05	0610	PBOC	\downarrow	.7	.7	.5	5.8	14.8	41.2
1/5/06	0605	SAFE	\uparrow	-.3	-.9	-.7	-17.1	0	-27.9
11/10/06	1450	PBOC	\downarrow	-.3	.2	.5	-3.2	-7.7	-25.1
1/20/07	0445	Premier	\uparrow	0*	.2*	0*	.3*	-4.3*	-1.1*
3/8/07	2155	Fin.Min.	\uparrow	.3	0	-.3	11.6	9.8	-9.5
3/15/07	2235	Premier	\downarrow	.7	.5	.5	-15.5	-25.9	-28.8
3/20/07	2150	PBOC	\uparrow	-.3	0	-.3	-4.8	-5.9	-11.0
11/6/07	2120	Adv.	\uparrow	.3	.5	.5	-15.5	-20.5	-14.4
7/27/08	0600	PBOC	\downarrow	0*	.7*	0*	25.9*	32.9*	92.7*
3/23/09	0210	PBOC	\downarrow	-2.6	-3.6	-3.6	2.5	-1.5	-30.6
3/23/09	0445	PBOC	\uparrow	-1.4	-2.4	-1.1	2.5	-1.5	-30.6
6/26/09	0450	PBOC	\uparrow	-.8	-.6	-1.1	0	-2.6	-4.1
3/8/10	2020	SAFE	\downarrow	.3	.2	0	2.2	5.9	-1.5
4/8/10	0355	NYT	\uparrow	.8	.2	-.2	-13.2	-37.7	-32.5
4/12/10	1955	Premier	\uparrow	-.5	-.6	-.7	5.9	20.0	14.6
5/10/10	2015	PBOC	\uparrow	.9	.6	.5	2.2	-5.9	-1.5
5/27/10	0210	SAFE	\uparrow	-.9	-.8	-.7	-4.7	-19.1	-59.9
6/19/10	0600	PBOC	\uparrow	6.3*	6.5*	4.8*	-25.7*	-67.3*	-98.1*
7/3/10	0305	PBOC	\downarrow	-1.2*	-.4*	-.7*	-1.5*	5.9*	13.5*
3/14/11	2250	Premier	\uparrow	-.8	-1.0	-1.2	-2.3	24.5	4.7
10/11/11	2040	PBOC	\uparrow	-.3	0	-.2	3.9	-3.1	-4.7
2/3/12	0305	Premier	\uparrow	.6	.6	.6	-.8	0	-4.0
3/6/12	0335	CIC	\uparrow	0	-.8	-1.0	14.3	23.0	39.2
3/11/12	2245	PBOC	\downarrow	0	0	0	30.9	34.8	37.3
8/30/12	0010	Premier	\uparrow	.1	.4	.2	0	2.8	2.3
5/6/13	0605	Premier	\uparrow	.4	.6	1.0	6.1	11.3	27.3
11/19/13	0210	PBOC	\uparrow	0	0	.2	-6.5	-10.6	-16.8

Table 2.1: Brief Description of the Event Set. Events are in chronological order, with the source of the announcement (broadly); the anticipated effect of the announcement on bond yields; the measured change in bond yields for futures contracts on Treasury bonds of three maturities within a centered one-hour event window; and the measured change in USD/RMB NDF prices for different contract settlement horizons. Asterisks denote events that occurred while the Treasury futures market was closed. See Appendix A for brief descriptions of the events.

2.5 Results

The combination of the model, identification technique, and high frequency data discussed above gives improved estimates of the effects of foreign official purchases of Treasuries. These results indicate that the effects are generally larger than previous research has found. I show that the impacts of Chinese official Treasury purchases are economically and statistically significant in Section 2.5.1, and also emphasize that the results are qualitatively consistent with economic intuition and benchmark theoretical models. In section 2.5.2, I use my estimates to approximate the total impact of the Chinese exchange rate peg on Treasury yields and Section 2.5.3 shows that my estimates of the impacts of official purchases on yields are generally larger than those in the existing literature. Finally, Section 2.5.4 provides evidence that traditional event study methods are not adequate to overcome the endogeneity bias in this case and that this paper's use of IDH meaningfully improves the results, especially for surprises at the 12-month horizon.

Before discussing the results, however, it is worth noting that there are essentially two parameters of interest from the model. First, there is the slope parameter α from Equation (2.2). This parameter measures the sensitivity of yields to exchange rates and is the only parameter which can be estimated in the single equation ES model. As such, it is the coefficient α which I will discuss in Section 2.5.4. A second, potentially more interesting parameter obtained from the two equation model in Equation (2.4) is the estimate of the impulse response of yields to exchange rates.⁶ The impulse response estimate will take into account the simultaneity modeled in Equation (2.4). Because I am interested in the full impact of policy shocks, I will focus on the impulse response coefficients wherever possible, which is in Sections 2.5.1 through 2.5.3.

⁶Note that because the model is of lag order zero, the impulse response is zero at all horizons other than in the period of the shock. Nonetheless, this is an impulse response function in the traditional VAR sense.

Note that the impulse response of yields to a one basis point shock to exchange rates is not α . If exchange rates rise by one basis point, the impact on yields is α , but this change in yields further affects exchange rates by the amount $\alpha\beta$, which again affects yields, and so on. Thus, the impulse response of yields to a one basis point exchange rate/policy shock, will be given by $\frac{\alpha}{1-\alpha\beta}$, the parameter in the lower left corner of the rotation matrix in Equation (2.3). Note that the impulse response of the exchange rate to a one basis point exchange rate shock is not one, but is rather $\frac{1}{1-\alpha\beta}$, the off-diagonal parameter in the rotation matrix in Equation (2.3). In discussing impulse responses below, I normalize the exchange rate shock such that the impulse response of exchange rates to their own shock is 100 basis points. This makes the discussion more intuitive and is consistent with common practice in the VAR literature to report impulse responses in this manner. With this normalization, which scales up the structural shock and its impact by a factor of $100 \times (1 - \alpha\beta)$, the impulse response of yields to an exchange rate/policy shock turns out to $100 \times \alpha$. Estimates of this parameter are shown in Table 2.2.

2.5.1 Impulse Response Estimates

My results indicate that foreign official capital flows substantially depress Treasury yields. Table 2.2 reports the contemporaneous impulse responses of yields to exchange rates in each of the nine possible models corresponding to Equation (2.4). Each of the nine models corresponds to a pairing of a Treasury futures contract (5-, 10-, or 30-year contract) with a currency forward contract (at the 1-week, 3-month, or 12-month horizon). As an example of the substantial size of the impacts I estimate, a 100 basis point surprise depreciation of the expected exchange rate 3 months in the future (such as a change from 7 to 7.07 yuan per dollar) would decrease 10-year Treasury futures-implied yields by 2.83 basis points. A similar surprise at the 12-month horizon would decrease such yields by 5.67 basis points. These effects are modest, but so is

the exchange rate surprise. For comparison, consider that over the sample period of January 2005 to April 2014, the 12-month-ahead expected USD/RMB exchange rate appreciated by about 22% versus the dollar.⁷ The model implemented here suggests that a surprise of that magnitude, if it occurred in a single day, would give rise to a total increase in 10-year Treasury futures-implied yields of 125 basis points. Of course, there was no single surprise of such magnitude, but it illustrates the point that the estimated impacts of surprises are large.

The impacts of exchange rate surprises on yields are all statistically significantly negative. Table 2.2 reports standard errors formed using the Delta Method applied to the Newey-West HAC estimator of the reduced form variance-covariance matrix with a lag length of 40 days.⁸ These standard errors indicate that nearly all of the coefficients are statistically significant at the 99% level.

The results are qualitatively consistent with economic theory and intuition along two dimensions.⁹ First, Table 2.2 indicates that exchange rate surprises at longer horizons have larger effects than surprises at short horizons. This is illustrated in the example above in which a surprise in 12-month-ahead expectations has an effect on 10-year futures twice as large as a 3-month-ahead surprise. This finding is consistent with the idea that surprises at longer horizons correspond to larger policy shifts, such as the change from a fixed to a managed floating regime. Such policy shifts correspond to large changes in expected future Treasury purchases, and thus should affect prices and yields to a greater extent. On the other hand, surprises at the 1-week horizon are more likely to represent short-term variation in policy, which would correspond

⁷Recall that these percent changes are approximated by log changes.

⁸The standard errors are not sensitive to the lag length chosen, and 40 was chosen based on the author's judgment.

⁹While theory and intuition give clear qualitative implications for the impacts of Treasury purchases on yields, such sources generally do not give clear quantitative implications. Indeed, this paper is part of a growing literature attempting to address this shortcoming of the theory. Given the lack of quantitative clarity on the impacts of purchases, I focus here on the qualitative implications of theory and then provide quantitative comparisons with the existing empirical literature below.

to smaller changes to the path of expected future Treasury purchases.

The results also indicate that surprises have larger effects on yields at the middle of the yield curve, where foreign officials are known to have the largest holdings. The average maturity of foreign official holdings over the sample period is between 3.5 and 4 years, though officials hold large quantities of securities out to about 10 years to maturity. The precise data on foreign official holdings by country is not publicly available, but analysts generally believe the PBOC is representative of foreign officials. Further, assuming the average maturity of the foreign official portfolio is roughly constant, which it appears it is, the average maturity of purchases must be greater than the average maturity of holdings to offset the aging of the existing holdings. Given that, ad hoc intuition and preferred habitat term structure models would suggest surprises to the expected path of Chinese official purchases should have larger impacts on yields in the 3 to 10 year range. Indeed, the estimates in Table 2.2 are consistent with this conjecture.

Finally, it is important to emphasize that the estimates in Table 2.2 cannot be used jointly. This is because they were generated by nine separate models with one yield and one surprise variable in each. Thus, we can imagine a hypothetical scenario in which the PBOC announces on a given day that it will appreciate its currency today, say from 7 yuan per dollar to 6.3. If the peg before and after the announcement is credible and expected to last forever, this would correspond to a 1,000 basis point (10%) surprise to exchange rate expectations at all horizons. However, we cannot sensibly sum up the effects of such a surprise at each of the three horizons to obtain the total effect of the policy shift on any given yield. As Table 2.1 suggests, surprises at each horizon are likely to be correlated with one another. This means that in regressions with only one surprise, the coefficient on that surprise may be larger than it otherwise would be, reflecting omitted variable bias that captures the effects of surprises at other horizons which are omitted from the model.

	Δ NDF		
	1-week	3-month	12-month
5-year Treasury future	-2.51*** (0.52)	-2.69*** (0.85)	-4.94** (2.03)
10-year Treasury future	-2.69*** (0.51)	-2.83*** (0.81)	-5.67** (2.33)
30-year Treasury future	-2.16*** (0.36)	-2.24*** (0.56)	-5.42*** (2.06)

Table 2.2: Impulse Responses of Treasury Yields to Exchange Rate Surprises. The contemporaneous impulse response of Treasury yields to a 1% (100bp) surprise exchange rate depreciation, expressed in basis points. *** denotes statistical significance at 99% level and ** denotes significance at the 95% level, based upon Newey-West HAC standard errors. Newey-West standard errors are in parentheses.

2.5.2 Measuring the Total Impact of the Chinese Exchange Rate Peg on Yields

The total impact of the Chinese exchange rate peg on US interest rates is of clear interest to economists, and this paper can provide estimates of this figure. There are potentially multiple ways in which one could leverage the results of this paper to estimate the total impact of the Chinese currency peg on US yields, and I will present one approach. In this section, I consider the hypothetical scenario in which the PBOC announced on the last day of May 2005 that it was dropping the exchange rate peg and allowing its currency to move to its equilibrium, free-floating value. I chose May 2005 because this was during the period of large Chinese Treasury purchases accompanied by low US interest rates. Since the stylized fact of low interest rates in the 2000s is one of the main motivating factors for this literature, May 2005 seems a natural choice. The results of this hypothetical exercise will provide a rough measure of the total impact of the Chinese currency peg and they will also allow comparison of my estimates of the impacts of policy surprises (measured in exchange rates) with other estimates from the literature (measured directly but at lower frequency, as actual Treasury purchase surprises). The comparison with the literature is considered in the

next section.

Translating the results from the impacts of relatively small policy shifts, measured in terms of exchange rate surprises at multiple horizons, to the hypothetical revaluation scenario will require several assumptions. First, I must assume that the estimate for the effect of an exchange rate surprise at one horizon will proxy sufficiently well for a surprise all horizons. As discussed above, each impulse response estimate is generated from a model corresponding to the exchange rate surprise at one horizon and presumably includes some omitted variable bias, capturing the impact of correlated exchange rate surprises at all horizons. Second, I must assume a reasonable size of the exchange rate surprise for the hypothetical scenario. To that end, Cline and Williamson (2008) summarize thirteen published studies which estimate the degree to which the RMB was undervalued against the dollar in real terms. Although I am concerned instead with a nominal exchange rate, I assume that the ratio of price levels remains constant so that proportional changes are the same for real and nominal rates (estimates of nominal undervaluation are scarce). Each of the summarized studies estimate the undervaluation for particular, but different, points in time between 2000 and 2007. The estimates for the RMB appreciation required to restore equilibrium range from 7% to 100% and average to 40%, with no trend up or down over the period of the estimates. To summarize the differing estimates, I will consider three revaluations: 7%, 40%, and 67%. Third, I will assume that the new, revalued exchange rate is expected to last indefinitely. This assumption implies that the spot and all forward exchange rates instantaneously jump from wherever they are on the last day of May 2005 to the new level of the spot exchange rate implied by the assumed revaluations of 7%, 40%, and 67%. Because some modest appreciation was apparently anticipated in late May 2005, the appreciation in forward exchange rates in each of the three scenarios is actually less than the appreciation in the spot rate.

With these assumptions in hand, I estimate economically substantial total impacts

	<i>7% Revaluation</i>		
	1-week NDF	3-month NDF	12-month NDF
5-year Treasury future	17	14	7
10-year Treasury future	18	15	8
30-year Treasury future	14	12	8
<hr/>			
	<i>40% Revaluation</i>		
	1-week NDF	3-month NDF	12-month NDF
5-year Treasury future	84	87	140
10-year Treasury future	90	91	160
30-year Treasury future	73	72	153
<hr/>			
	<i>67% Revaluation</i>		
	1-week NDF	3-month NDF	12-month NDF
5-year Treasury future	129	134	227
10-year Treasury future	138	141	260
30-year Treasury future	111	112	249

Table 2.3: Estimated Impacts of the Chinese Currency Peg. Impacts of revaluation surprises in each of three currency forwards on each of three Treasury yields, in basis points, for three different sizes of revaluation.

of the Chinese currency peg (Table 2.3). In the baseline case, suppose that achieving the equilibrium exchange rate required an instantaneous 40% appreciation of the spot rate, and further assume that all forward rates instantly jump to this new level of the spot rate. My estimates of the impact of exchange rate surprises indicate that the 5-year Treasury yield would jump by 84 to 140 basis points, the 10-year yield would jump by 90-160 basis points, and the 30-year by 73 to 153 basis points. The range of estimates for each yield arises because surprises at the 1-week, 3-month, and 12-month horizon each generate a different estimated impact. Generally, surprises at longer horizons generate larger impacts. Table 2.3 also shows the smaller impacts of a 7% revaluation and the larger impacts of a 67% revaluation.

These impacts are sufficiently large that foreign demand (and even just demand from Chinese official institutions) could explain the period of low long-term interest rates in the mid-2000s. Indeed, these estimated impacts are larger than existing es-

timates of the extent to which yields were “too low” in the mid-2000s. In particular, Bernanke et al (2004) and Rudebusch et al (2006) estimate empirical term structure models that control for standard macroeconomic variables such as the stance of monetary policy and inflation, producing commonly-cited heuristic measures of the degree to which yields were unusually low. They find that the 10-year Treasury yield in the mid-2000s was lower than might be expected by about 50-80 basis points, depending upon the particular point in time and model used. This range is often cited as the discrepancy which needs to be explained, perhaps by foreign official demand for Treasury securities. My estimates suggest that Chinese official demand alone could account for this discrepancy, ignoring other foreign buyers of Treasuries. Thus, by my estimates, total foreign demand would have an even larger impact on Treasury yields, though by how much is unclear. China was the single largest buyer of Treasury securities at the time, having represented about 40% of all net foreign Treasury purchases in the 12-month period to May 2005. Nearly all Chinese Treasury purchases should be official purchases, given China’s closed capital account, though precise estimates of the official share of the Chinese purchases are not available. Further, a significant portion of the remaining 60% of foreign purchases in the 12 months to May 2005 are private purchases, which might be expected to have a smaller impact on yields due to the greater demand elasticity of private buyers (Beltran et al (2013)). Finally, it is worth noting that the impact effects that I estimate need not equal the impacts over longer horizons. Indeed, Abe (2007) implements an event study and estimates smaller initial impacts than I do, but also finds that the impacts tend to attenuate as time progresses. Nonetheless, my estimates suggest that Chinese demand for Treasuries substantially depressed yields during the mid-2000s, and more generally that foreign demand for Treasuries has large impacts on Treasury prices and yields.

2.5.3 Comparison with Estimates from the Literature

The hypothetical scenario in the previous section allows me to compare the magnitude of my results with those from the existing literature. Outside the context of the above hypothetical scenario, direct comparison with the existing literature is difficult, because this paper estimates the impacts of policy surprises measured in terms of exchange rate changes. The existing literature considers the impacts of actual Treasury purchases, either in dollar terms or as a share of marketable Treasuries, so some method of translation between exchange rates and dollars is needed.¹⁰ If I add one assumption to those needed for the above scenario, I can make that translation. In particular, I assume that Chinese purchases of Treasuries would be zero if their exchange rate were at its equilibrium value. That assumption allows me to provide a dollar figure for Treasury purchases arising from the Chinese currency peg. I already have a measure of the exchange rate surprise corresponding to the peg, so I am now able to translate between the two. Of course, assuming Chinese official Treasury purchases would go to zero is a strong assumption, as some Chinese official Treasury purchases likely reflect high private savings in China being mediated through the official sector due to the closed capital account. Such purchases may not vanish in the absence of the peg. If purchases were to remain positive with the end of the peg, the dollar value of purchases would change less in response to the end of the peg, and the existing literature would suggest smaller impacts of the peg on yields than discussed below.

Comparing my results with those from the literature, this paper finds generally larger impacts of purchases. Based on the results in Table 2.3 for the baseline case of a 40% appreciation, I will take 100 basis points to be this paper's benchmark impact of the Chinese peg on all three yields. I first compare my results with the

¹⁰Of, course there are several other issues with comparison, but I largely ignore these complications for the purposes of this discussion. For instance, my estimates are for intradaily yield changes, while many papers in the literature are for monthly yield changes.

four existing papers which estimate the impacts of 12-month accumulated Treasury purchases on yields at the monthly frequency. First, Warnock and Warnock (2009) estimate that \$100 billion dollars of accumulated official purchases depress 10-year Treasury yields by 68 basis points. Given that total Chinese purchases in the 12 month period to May 2005 were about \$80 billion and assuming all Chinese purchases were official purchases¹¹ undertaken to maintain the peg, this suggests Warnock and Warnock estimate impacts of about 55 basis points in the scenario. This estimate is below my benchmark of 100 basis points, though within the range of estimates if the appreciation needed to reach equilibrium is less than 40%. One might assume that Warnock and Warnock would estimate relatively small impacts given that they do not use an identification scheme, arguably biasing their results toward zero. However, Warnock and Warnock's findings are not small relative to the rest of the literature. Similar calculations suggest that Beltran et al (2013) estimate impacts of 30-50 basis points on the 5-year yield in a model identified by instrumental variables. Again, this is smaller than my benchmark impact of the scenario. Third, Chapter 1 of this dissertation uses sign identification in a VAR to estimate that the scenario would increase 5-year yields by about 75 basis points and the 10-year yield by about 60 basis points. However, the sign identification procedure yields wide confidence intervals that easily overlap the ranges in this paper, so this chapter and the previous find estimates of a broadly similar magnitude. Finally, Rudebusch et al (2006) estimate that foreign Treasury purchases have negligible impact on yields, though their result is an outlier in the literature.

Additionally, there are a couple of higher frequency studies to consider which estimate effects a bit smaller than mine. Bernanke et al (2004) estimate effects of about 55 basis points from a daily ES model for the case of Japanese official interventions in the early 2000s. Lastly, McCauley and Jiang (2004) use weekly

¹¹Data on official Treasury purchases by China is not publicly available, though China's closed capital account would suggest nearly all Chinese Treasury purchases were official purchases.

capital flows data and find effects a bit larger than most of the literature and on the lower end of my estimates, in the neighborhood of 80 basis points.

Thus, this paper finds impacts which are generally larger than in the existing literature, arguably because the use of IDH allows me to overcome the endogeneity bias discussed in Section 2.1. It is worth noting that Table 2.4 indicates that endogeneity is present and does indeed bias incompletely identified estimates toward zero.

2.5.4 Comparison with Event Study Estimates

As a final exercise, I compare the estimates of α from IDH with the estimates generated by simple ES methods. This comparison suggests that ES methods appear not to adequately identify the models which include surprises measured at the 12-month horizon. The first two columns in Table 2.4 show that IDH produces meaningfully different estimates of the coefficients than ES. In all cases, the estimates of α are larger in absolute value (more negative) when estimated by IDH. For surprises at the 12-month horizon, the differences are very large and statistically significant. Significance is assessed using the Hausman test, which tests the null hypothesis that the ES identifying assumption from Section 2.2.1 is true (and thus both the ES and IDH estimators of α are consistent, but ES is efficient) against the alternative that the ES identifying assumption is violated (in which case the IDH estimator is consistent and the ES estimator is not).

This finding suggests that simple ES methodology is an inadequate treatment for endogeneity in this case. That is, I would argue that the ES estimates of the coefficients are closer to zero because of remaining endogeneity bias. Indeed, I estimate that β from Equation (2.2) is positive in all models, which means that endogeneity bias in the ES estimates should be positive, biasing those estimates toward zero. It is worth noting here that Rigobon and Sack (2004) present similar findings regarding bias in ES estimates of the impacts of US monetary policy shocks on various asset

Treasury future	NDF	IDH	ES	Hausman Test
5-year Treasury future	1-week NDF	-2.51*** (0.52)	-2.39*** (0.34)	0.11
5-year Treasury future	3-month NDF	-2.69*** (0.85)	-2.43*** (0.57)	0.17
5-year Treasury future	12-month NDF	-4.94** (2.03)	-1.78 (1.43)	4.91 [†]
10-year Treasury future	1-week NDF	-2.69*** (0.51)	-2.57*** (0.34)	0.10
10-year Treasury future	3-month NDF	-2.83*** (0.81)	-2.58*** (0.56)	0.18
10-year Treasury future	12-month NDF	-5.67** (2.33)	-1.53 (1.66)	6.60 [†]
Treasury bond future	1-week NDF	-2.16*** (0.36)	-2.10*** (0.26)	0.07
Treasury bond future	3-month NDF	-2.24*** (0.56)	-2.10*** (0.43)	0.16
Treasury bond future	12-month NDF	-5.42*** (2.06)	-1.31 (1.20)	6.16 [†]

Table 2.4: Comparing IDH and ES Estimates of α . All parameters are scaled up by a factor of 100 to eliminate zeros. *** denotes statistical significance at 99% level and ** denotes significance at the 95% level, based upon Newey-West HAC standard errors. Newey-West standard errors are in parentheses. Rightmost column shows the Hausman test statistic assessing the significance of the difference between the two estimates of α . The critical value for 95% significance is 3.84 and [†] denotes this significance.

prices.

2.6 Conclusion

This paper provides new evidence indicating that the effects of foreign official purchases are quite large. By creating a novel measure of the surprise contained in Chinese policy announcements, employing high frequency data, and using the method of identification by heteroskedasticity, I produce new estimates of the effects of Chinese official purchases of Treasuries. In so doing, I overcome endogeneity bias present in the existing empirical literature. This endogeneity biases the estimates in other papers toward zero, so that I find quantitatively larger effects than most previous

work. I estimate that Chinese purchases of Treasury securities made in the pursuit of exchange rate goals depressed 10-year Treasury rates by perhaps 100 basis points, though some smaller or substantially larger impacts are possible. The effects on 5-year Treasury yields are comparable and the effect on 30-year yields is estimated to be a bit smaller.

These results offer insights into a couple of ongoing debates in economics. First, there has been considerable discussion of the period of unusually low long-term interest rates in the US during the mid-2000s, often referred to as the bond-yield “conundrum” (beginning with Greenspan (2005)). Many observers have cited foreign official purchases as a major cause of the conundrum. However, the empirical work on the topic has yet to conclude that this is the case, because of widely varying estimates of the impacts of purchases on yields and because of probable endogeneity bias in many of those studies. My results indicate that foreign official Treasury purchases played a larger role in the conundrum than most other papers find and that foreign demand can explain the conundrum. Additionally, I provide evidence of endogeneity bias in event study estimates of the impacts and argue that many existing studies suffer from endogeneity bias. This paper can also contribute to the large and growing literature on the effects of LSAPs. My results suggest that an official institution (be it the PBOC or the Fed) can have a large impact on Treasury yields by buying Treasury securities in large quantities. There are certainly reasons to believe that Treasury purchases in the context of quantitative easing might have different effects than purchases in pursuit of an exchange rate peg, but my results still indicate that quantitative easing is effective.

Finally, these results suggest that foreign official institutions have the ability to significantly affect credit conditions in the US, so that as global capital markets continue to become more integrated, the Federal Reserve will have to act more aggressively to offset foreign influence. This finding is crucial to the conduct of monetary policy.

Indeed, some commentators argue that credit conditions were loose during the mid-2000s due to the influence of foreign official institutions, in spite of the fact that the Federal Reserve was raising short-term interest rates. These commentators suggest that the loose credit conditions may have fueled asset price bubbles (for example, in long-term interest rate-sensitive sectors like housing) which burst during the financial crisis. Clearly, understanding the effect of foreign official purchases of Treasury securities is important for the effective conduct of monetary policy. This paper provides new insight on this topic.

CHAPTER 3

Extracting Treasury Flows as a Latent Variable

3.1 Introduction

Economists and financial market participants are keenly interested in international financial flows. Analysts are especially interested in foreign activity in the US Treasury market, both because of the importance of the Treasury market and because foreigners are such large participants in the market. Foreigners have owned more than half of the stock of Treasury notes and bonds in the hands of the public over much of the past decade. In monitoring and studying foreign activity in the Treasury market, analysts rely on a variety of data sources to reveal exactly how many Treasury securities foreigners are buying or holding and the value of those securities. Regardless of the particular source, there are arguably three critical qualities of the data on foreign purchases on which all analysts agree. Ideally, the data would be accurate, available in a timely manner, and available at high frequency. The argument for accuracy is obvious.

Timely data is important to help market participants and policymakers understand what is occurring in real time, and the interest in timely data is revealed routinely in the financial press. For example, when foreigners appear to be selling Treasury securities, analysts and the press are quick to take note and express concern about the risk of higher US interest rates if the sales continue (See Johnson (2013) and Zeng (2014)). Similarly, when foreign officials appear to be buying Treasuries, US officials are quick to express concern about official intervention in foreign exchange

markets (Chandler (2014) and US Department of the Treasury (2014)). Unfortunately, timeliness in Treasury purchases data has typically come at the expense of accuracy. Accurate weekly data from the Federal Reserve Bank of New York covers only a fraction of the total foreign activity in the Treasury market and more comprehensive monthly measures of net foreign purchases are known to exhibit several errors and biases. Comprehensive, high quality data is available only at the annual frequency and with a substantial delay (Bertaut and Tryon (2007)).¹

Finally, analysts also benefit from the availability of high-frequency data. As mentioned above, there is partial data on foreign purchases and holdings available at the weekly frequency, but comprehensive data is only available at the monthly frequency or less. Economic analysis would benefit from data at higher frequencies than are currently available. For instance, event studies on the impacts of foreign purchases of Treasuries on Treasury yields could use a more complete measure of foreign purchases at the daily frequency. Bernanke, Reinhart, and Sack (2004) and Abe (2007) conduct event studies on the impact on Treasury yields of Japanese Ministry of Finance Treasury purchases in the early 2000s because the Ministry of Finance reports its purchases at the daily frequency. Lacking such high frequency data for other purchasers or time periods, these event studies must focus on Japanese purchases over a short period of time. Clearly, regardless of the frequency, economic research also demands that the data be accurate and, perhaps to a slightly lesser extent, timely.

In order to improve the accuracy of data on Treasury flows, to improve the trade-off between accuracy and timeliness, and to provide a high-frequency (daily) measure of flows, this paper uses the Kalman Filter to construct a new measure of net cross-border Treasury flows. I model Treasury flows as comprised of two unobserved daily

¹The marginal cost of timeliness in terms of accuracy has fallen somewhat in the past eighteen months with the introduction of a newer, apparently more reliable survey methodology by the Treasury, but the point remains that there are a variety of timely but potentially misleading sources of information on foreign Treasury purchases and these sources often disagree meaningfully with one another. Warnock (2010) includes a discussion of a particularly remarkable example of such a disagreement.

series: purchases of Treasury securities (“outright” purchases or sales) and valuation changes on the stock of foreign holdings (valuation flows). The unobserved series are then extracted from several mixed-frequency, noisy, observed data series. The observed data I use include two different monthly series from the Treasury International Capital (TIC) database, an annual series from TIC, daily exchange rate data, and daily Treasury yield data (combined with information on the duration of foreign holdings, taken from TIC).

This approach improves upon the available data along all three dimensions discussed above. First, it offers an accurate description of Treasury flows and foreign Treasury holdings in the sense that it is consistent (within the context of a statistical framework) with the available, relevant data series. Ultimately, because we do not observe the true data, accuracy is difficult to assess. However, the series extracted in this paper conform to a reasonable and well-understood time series model, match the behavior of the most trusted annual data on foreign purchases, and behave similarly (though with some informative deviations) to the currently most trusted monthly series.² Second, this paper improves the trade-off between timeliness and accuracy. I am able to provide estimates for flows and foreign holdings extrapolating forward from the most recent annual survey (unlike previous practices) and the estimates reflect information from a greater number of observed time series than previous estimates. Finally, my approach produces an estimate for daily flows and holdings of Treasury securities. This series is consistent with observed lower frequency measures of purchases and holdings. The daily flows series is also consistent with daily data on Japanese Ministry of Finance foreign exchange interventions, one of the only available sources of raw daily flows data.

²Over most of the sample, the monthly series regarded as the most reliable would be the data generated by Bertaut and Tryon (2007) using a simpler time series model and fewer observed data series than I use in this paper. Since late 2011, the Treasury has collected monthly data on foreign holdings which appears, based on evidence available to date, to be fairly accurate (Brandner, Cai, and Judson (2012)).

The rest of the paper is organized as follows: Section 3.2 discusses the available data on foreign purchases and holdings and the existing modifications. Section 3.3 presents the conceptual framework, the state space representation, and the estimation technique for the new approach in this paper. Section 3.4 presents the results and compares them to existing data and relevant benchmarks. Section 3.5 concludes.

3.2 Raw Data and Existing Improvements

To provide context for the contribution of this paper and also to provide background information on the data I will employ, I must now discuss the available data on Treasury flows. After discussing the data and its shortcomings, I will provide a brief overview of the existing methodology for improving the quality of the available data. This methodology, from Bertaut and Tryon (2007), will serve as a useful benchmark for the series which I estimate in this paper and is also the main measure of flows with which my series competes.

3.2.1 Raw Measures of Treasury Flows

As suggested in the introduction, there are four imperfect measures of Treasury flows available to analysts. There are annual and (recently) monthly measures of the stock of foreign holdings, a monthly measure of transactions (ie, outright purchases only), and a weekly measure of a subset of the stock of foreign holdings. The weekly series comes from the Federal Reserve Bank of New York and all three lower frequency series are from the TIC database.

The first series is an annual measure of the stock of foreign holdings of US Treasury debt, which comes from the TIC survey of foreign holdings of US securities. This series will be referred to henceforth as the “SHL” series based on the name of the survey forms used in the collection of the data. The SHL series are published as a

snapshot of the value of the stock of foreign holdings as of June 30th of each year (the “survey date”). Preliminary results from the survey become available in the February following the survey date and final results are published on April 30th following the survey date, a delay of 10 months. The survey includes data on the breakdown of Treasury holdings by investor type (official and private), by country, and by maturity.³ Both because the data is believed to be of high-quality (carefully collected at the level of individual securities from custodians, issuers, and investors) and because no better measure of the truth currently exists, analysts typically treat the SHL data as more or less free of error. Clearly, the Form SHL stock data can be used to create a measure of annual flows (the sum of outright purchases/sales and valuation flows) by taking first differences.

A second series, available beginning only in late 2011, is a monthly measure of the stock of foreign holdings from TIC Form SLT. It is similar to the annual measure of the stock and is intended to improve the trade-off between timeliness and accuracy. Based on available evidence, the SLT data appears to be of relatively high quality and provides a similar characterization foreign purchases and holdings to the annual SHL data, though some differences remain. As in the case of the annual stocks above, these monthly stocks can be differenced to obtain monthly flows.

The third series is a monthly measure of net cross-border transactions (purchases and sales only) measured by TIC Form S. Form S transactions are stated as the net, monthly cross-border purchases and sales of securities at end-of-month prices. The series only measures outright purchases (and not valuation changes) and only captures transactions between US residents and foreign counterparties (that is, it excludes transactions between only foreign counterparties). Form S data are desirable both because of their higher frequency and because they are available with a delay of only about a month, making them the most timely data on flows available from TIC.

³It also includes similar data for several other asset classes: asset-backed securities, corporate bonds, and equity.

However, Form S transactions data cannot be easily accumulated into a measure of stocks (and they are not directly comparable to Form SHL or SLT data) for a couple of reasons. First of all, Form S data exclude valuation changes in the stock of foreign holdings, so separately performing a valuation adjustment would be necessary to make the series comparable and create monthly stock series from the Form S data. Additionally, there are several sources of noise or error in the data, not all of which are fully understood. At least one is that transactions costs are included in the measure of transactions. Additionally, Bertaut and Tryon (2007) find evidence of other, unknown errors.⁴ Given these problems, the monthly transactions data is typically treated as very unreliable until it has been adjusted to be consistent with annual Form SHL data (including the addition of valuation adjustments).⁵

The fourth and final measure foreign holdings comes from the Federal Reserve Bank of New York and is published weekly in the Federal Reserve's H4.1 release. It is the dollar value of Treasury securities held custodially by the Federal Reserve Bank of New York for foreign official and international institutions. The data are desirable due to their high frequency, timely release (with a delay of only one day), and presumed accuracy. However, the custody holdings data cover only about 60% to 75% of foreign official holdings of Treasury securities and entirely exclude private holdings. For this reason, analysts typically discount the custody holdings data and rarely use it in academic studies.

3.2.2 Existing Approach to Improving the Raw Data

Given the various sources of data, each with their own shortcomings, it is natural that economists would develop a systematic approach to combining the different sources, creating a hybrid series which exploits the advantages of the underlying raw series.

⁴For asset-backed securities, repayments of principal are ignored, also.

⁵The Form S data also exhibit severe biases in the breakdown of net purchases by country and by investor type.

Thus far, the literature has focused on a single approach to generating an improved measure of monthly stocks, based on two of the raw series discussed above: Form SHL annual stock and Form S monthly transactions data, as well as Treasury pricing data. This approach is best exemplified by Bertaut and Tryon (2007), though earlier forms were presented in Thomas, Warnock, and Wongswan (2004), Bertaut, Grier, and Tryon (2006), and Warnock and Warnock (2009). The Bertaut and Tryon (BT) method does not use Form SLT data because they were not available at the time and excludes data from the New York Fed presumably due to the shortcomings discussed the previous section.⁶ The BT data, available from the Federal Reserve, ends in June 2011, shortly before the TIC Form SLT data begins.

The BT method begins with the assumption that the annually observed SHL stocks are accurate and then uses the monthly transactions data and Treasury pricing data to extrapolate monthly stocks from one SHL survey date to the next. In practice, this amounts to adding measured (Form S) transactions and the valuation change (estimated using a standard index of Treasury prices) to the previous month's stock. The process is repeated each month, beginning from an SHL survey value, until the next SHL survey date. Unsurprisingly, the resulting extrapolated monthly stock series generally does not equal the next SHL stock measure. Since the latter is assumed to be the truth, one must find a method for smoothing this gap over the previous year's flows (since the last observation of the truth in the form of an SHL survey), although the observer does not know in which month the errors occurred. Bertaut and Tryon model the resulting gap between extrapolated and SHL stocks, thought to arise from errors in measuring the valuation changes, the inclusion of transactions costs in reported transaction values, and other sources, as proportional to net transactions.

⁶Beltran, Kretchmer, Marquez, and Thomas (2013) adjust the BT series using confidential, country-level data on the New York Fed's custody holdings, but neither their adjustment technique nor their data are publicly available.

The resulting series can be written mathematically as

$$\hat{S}_t = \hat{S}_{t-1}(1 + \hat{\pi}_t) + \hat{N}_t + \gamma_t \text{gap}_t, \quad (3.1)$$

where hats denote series that are observed or extrapolated with the potential for error. \hat{S}_t is the value of the stock of foreign holdings at the end of month t , $\hat{\pi}_t$ is the percentage change in Treasury prices over month t (measured by a standard price index), and \hat{N}_t is the value of monthly net transactions measured by the TIC form S. The gap between the extrapolated and SHL stock is distributed over each year using the weighting function γ_t . The weighting function is time-varying for two reasons. First, the gap is distributed across months in proportion to each month's net transactions, which are of course time-varying. Second, the gap observed at the annual frequency includes both observation errors in the monthly transactions data, \hat{N}_t , and the valuation changes on those observation errors which accumulate between the time of the monthly observation error and the annual observation of the gap. The share of the annual gap attributed to any month must be valuation-adjusted to account for the latter.

This method greatly improves the quality of available data on foreign holdings or purchases, but has several shortcomings that I address in this paper. First, the BT series only uses three sources of information to estimate the value of unobserved foreign holdings: TIC Form SHL surveys, TIC Form S surveys, and Treasury pricing data. In addition, the BT method uses Treasury pricing data only to perform a simple accounting exercise to estimate valuation changes in the foreign portfolio. A growing literature indicates that purchases of Treasuries have substantial impacts on Treasury prices, so variation in Treasury prices may also contain information regarding Treasury flows beyond the information that can be extracted by this accounting exercise. My method allows for Treasury price changes to inform estimates of flows

both through an accounting or valuation channel and through the price impact of purchases on yields. My method also incorporates information from exchange rate movements and the recently created TIC form SLT data. A second shortcoming of the BT method is that it only generates monthly estimates of stocks or flows. For many purposes, higher frequency data is desirable. A state space model and the Kalman Filter provide a natural method to apply mixed frequency data, including daily data, to estimate daily stocks and flows. Finally, the BT method is likely to provide a noisier measure of flows than the truth because of the valuation adjustment process. In Equation (3.1), \hat{S}_{t-1} includes the accumulation of Form S transactions data, and the accompanying measurement errors, since the last SHL survey date. Thus, the BT method effectively valuation adjusts the noise in the Form S series, which should result in a noisier extrapolated flows or stocks series. It is worth noting that this process will not affect flows or stocks over longer horizons, since the series is constrained to match the SHL series. It is also worth noting that distributing the extrapolation gap across months between surveys does not eliminate this noise, as the gap reflects the accumulated errors from all twelve months between each SHL survey, whereas the valuation adjustment process in any given month adjusts the errors month-by-month.⁷ By employing a Kalman Filter, I remove this noise prior to applying valuation adjustments. As expected, I obtain a series with slightly lower variance. Third and finally, this paper applies a well-understood and more rigorous time series model to estimate Treasury flows and reveals a few cases where previously existing estimates of flows may have been misleading.

Having reviewed the sources of raw data and the existing techniques for improving the data, I will now present my empirical approach.

⁷This problem could be more complicated if errors are allowed to exhibit serial correlation, but both this paper and Bertaut and Tryon assume a serial correlation of zero.

3.3 My Empirical Methodology

In this section, I present the conceptual framework behind my new measure of Treasury flows, then present the data and model used to implement that framework empirically.⁸

3.3.1 Conceptual Framework

To motivate the state space model discussed below and to fix ideas, consider a simple conceptual framework for cross-border Treasury flows. There are (potentially) flows on each US business day.⁹ On such days, total Treasury flows can be decomposed into two parts: outright purchases/sales of Treasury securities (at current prices) by foreigners and valuation changes in the stock of foreign holdings as a result of changes in the market prices of Treasury securities. Mathematically,

$$f_t = o_t + v_t, \tag{3.2}$$

where o_t are daily outright purchases/sales and v_t are daily valuation changes. Loosely, outright purchases are the current price multiplied by the daily change in the number of securities held by foreigners and valuation changes are the quantity of securities held by foreigners multiplied by the change in the price on that day. It is worth noting that by this definition, daily flows, f_t , are the same as the daily change in the current value of the stock of foreign holdings of Treasury securities:

$$\Delta s_t = f_t = o_t + v_t.$$

⁸Arouba, Diebold, and Scotti (2009) use similar methods to generate high-frequency, real-time estimates of real economic activity.

⁹For the purposes of this paper, US business days are defined to be every day for which the Federal Reserve produces end-of-day Treasury yield data according to the methodology of Gürkaynak, Sack, and Wright (2006). This definition yields a series of business days nearly identical to that from other common definitions.

This paper is primarily concerned with obtaining an estimate of daily flows, $f_t = \Delta s_t$, though I will separately obtain o_t and v_t , and they may be of interest in their own right.

While daily flows are themselves never observed, there are several related series that are observed at various frequencies. Consider a generic series i observed on day t and call it y_t^i . This series can be expressed as a linear function of a constant, the two components of flows, a vector other explanatory variables, and an error term:

$$y_t^i = \gamma_0^i + \gamma_1^i o_t + \gamma_2^i v_t + \Gamma^i X_t + u_t^i, \quad (3.3)$$

where I assume that $u_t^i \sim iid\mathcal{N}(0, \sigma_{u^i}^2)$.

The series y_t^i may not be observed every day, so denote the series observed at lower frequency by \tilde{y}_t^i . The expression for \tilde{y}_t^i which is consistent with Equation (3.3) will depend upon whether \tilde{y}_t^i is a stock or a flow variable. If \tilde{y}_t^i is a stock variable, then it is just the value that y_t^i takes on the day t on which it is observed. Thus, for those days when y_t^i is observed, $\tilde{y}_t^i = y_t^i$, and so the expression for \tilde{y}_t^i is just Equation (3.3). On those days when y_t^i is not observed, \tilde{y}_t^i is missing (“NA”). That is,

$$\tilde{y}_t^i = \begin{cases} y_t^i = \gamma_0^i + \gamma_1^i o_t + \gamma_2^i v_t + \Gamma^i X_t + u_t^i, & \text{if } y_t^i \text{ is observed} \\ \text{NA}, & \text{otherwise.} \end{cases} \quad (3.4)$$

If \tilde{y}_t^i is instead a flow variable, then it is the sum of the daily flows y_t^i since \tilde{y}_t^i was last observed:

$$\tilde{y}_t^i = \begin{cases} \sum_{j=0}^{n-1} y_{t-j}^i = \gamma_0^i + \gamma_1^i \sum_{j=0}^{n-1} o_{t-j} + \gamma_2^i \sum_{j=0}^{n-1} v_{t-j} + \Gamma^i \sum_{j=0}^{n-1} X_{t-j} + \varepsilon_t^i, & \text{if } y_t^i \text{ is observed} \\ \text{NA}, & \text{otherwise,} \end{cases} \quad (3.5)$$

where n is the number of days since the last observation of the flow. The error term ε_t^i is the sum of the i.i.d. daily errors and is thus i.i.d. $\mathcal{N}(0, \sigma_{\varepsilon^i}^2)$, where $\sigma_{\varepsilon^i}^2 = n\sigma_u^2$.

I will cast these basic relationships in a state space form and extract measures of daily outright purchases/sales (o_t) and of daily valuation changes (v_t) using the Kalman Filter. The sum of these two series is daily Treasury flows, f_t , which can be accumulated to obtain stocks or flows at various frequency. The Kalman Filter is well-suited to this task for at least two reasons. First, it is a well-understood time series technique for obtaining unobserved or latent series from the variation in related, observed series. This is precisely my goal in this paper. Second, the Kalman Filter can easily accommodate the varying frequency of the observed data and the resulting large number of missing observations. These benefits and the implementation of the model will be discussed in greater detail in Section 3.3.3.

3.3.2 Data and Measurement Equation Relationships

Before discussing the implementation of the state space model, I will discuss the data and how I model it as a function of the unobserved components of flows. I use a total of six time series related to Treasury flows from July 2002 through January 2014, all of which, I will argue, are functions of either o_t or v_t . Three are daily series derived from asset prices and three are lower-frequency measures of flows derived from the TIC database. Those series are:

- **Daily approximate valuation changes:** \hat{v}_t . The daily change in the value of foreign holdings of Treasury securities, v_t , can be written as

$$v_t = (\% \Delta p_t) s_{t-1},$$

where p_t is an index of the price of foreign-held Treasuries. I approximate the percent price change using the standard duration-based approximation for

capital gains:

$$\% \Delta p_t = -\delta^{\text{mod}} \Delta i_t,$$

where I assume δ^{mod} is constant at 4.2, which is approximately the average duration of the foreign portfolio over my sample period. Ideally, I would use the exact duration on each day. However, the duration of the portfolio is never observed. Only the breakdown of maturity into rough bins is ever observed, and this observation only occurs once a year. In any event, the maturity structure, and thus probably the average duration of foreign holdings, appears to be quite stable. For Δi_t , I use the change in the five-year, smoothed, zero-coupon Treasury yield from Gürkaynak, Sack, and Wright (2006), as this is the closest maturity to the average maturity of foreign holdings and fits the data best in unreported regressions.

Finally, I must approximate s_{t-1} , as that is also not observed. Indeed, if it were observed, this entire exercise would be unnecessary. I linearly interpolate the SHL stocks at the daily frequency to produce an approximate daily stock series. This approximation to the daily stock of foreign holdings allows my valuation change measure to correctly capture the sharp upward trend in foreign holdings, and thus in the volatility of daily valuation changes, over my sample period. However, it does not take account of the relatively small impact of intra-year deviations from this upward trend.

These assumptions give rise to an approximate daily valuation change series \hat{v}_t , which I assume is equal to the true valuation change series v_t :

$$\hat{v}_t = v_t \tag{3.6}$$

In principle, I should add an error term to Equation (3.6), resulting in the

equation

$$\hat{v}_t = v_t + \varepsilon_t^v.$$

However, doing so causes the Kalman Filter to attribute nearly all of the variation in the approximated valuation adjustment series, \hat{v}_t , to ε_t^v rather than to actual valuation adjustments, v_t . This is because the error term is unrestricted while v_t is constrained to satisfy summation constraints discussed below. Thus, the filter assigns nearly all the variance from the observed left-hand-side to the second of the two unobserved right-hand-side series, ε_t^v . While it is surely the case that there should be an error term with some small variance, I cannot know what that variance should be. I argue that setting the variance of ε_t^v to zero is closer to the truth than the answer the Kalman Filter picks, which implies that there are virtually no valuation changes. Thus, I use Equation (3.6) with no error term.

- **Daily five-year yield change:** $\Delta i_{5,t}$. I include the daily change in the 5-year Treasury yield as it may provide information on flows over and above the information it provides in the valuation adjustment exercise described immediately above. There is a large and growing literature which suggests that foreign Treasury purchases cause changes in Treasury yields or prices (see Warnock and Warnock (2009), Beltran et al (2013), and Chapters 1 and 2 of this dissertation). In short, Treasury purchases affect demand for US Treasury securities, which affects their price and yield. Thus, changes in Treasury yields contain information regarding purchases. Specifically, a decline in yields on any given day might signal large foreign purchases of Treasuries and vice versa. Given the findings of the above-mentioned literature, I model the change in the five-year

yield as

$$\Delta i_{5,t} = \beta_1 o_t + \varepsilon_t^1, \quad (3.7)$$

where $\varepsilon_t^1 \sim \mathcal{N}(0, \sigma_{\varepsilon^1}^2)$.

While it may be desirable, in principle to include additional yields, I do not because the majority of the variation in Treasury yields are level shifts that are mostly common to all yields and because adding more yields only increases the number of parameters to estimate. Given that five years is close to the average maturity of foreign holdings over the sample period, it is the natural candidate for the single yield to include in the model. Additionally, Chapters 1 and 2 find that the impacts of purchases are largest on five-year yields.

- **Daily log-changes in exchange rates:** $\Delta \log(e_t)$. Given that many foreign Treasury holdings are in the form of foreign exchange reserves, variation in exchange rates should contain information on Treasury flows. Hence, I model daily log-changes in the Federal Reserve's broad dollar index as a function of both outright purchases and valuation changes on the given day:

$$\Delta \log(e_t) = \beta_2 o_t + \beta_3 v_t + \varepsilon_t^2, \quad (3.8)$$

where $\varepsilon_t^2 \sim \mathcal{N}(0, \sigma_{\varepsilon^2}^2)$.

- **Monthly Form S transactions:** \hat{o}_t^S . As discussed above, the TIC Form S transactions are a noisy measure of outright purchases and sales, o_t , over the month. Thus, consistent with Equation (3.5), I model Form S transactions as

$$\hat{o}_t^S = \sum_{j=0}^{n^m-1} o_{t-j} + \varepsilon_t^3, \quad (3.9)$$

where n^m is the number of business days in the month (which obviously varies from month-to-month) and $\varepsilon_t^3 \sim \mathcal{N}(0, \sigma_{\varepsilon^3}^2)$.

- **Monthly Form SLT flows:** \hat{f}_t^{SLT} . The monthly TIC Form SLT survey provides a noisy measure of the stock foreign holdings at the end of each month, so first-differencing the data yields a noisy measure of flows. Thus, I model Form SLT flows as

$$\hat{f}_t^{SLT} = \sum_{j=0}^{n^m-1} o_{t-j} + \sum_{j=0}^{n^m-1} v_{t-j} + \varepsilon_t^4, \quad (3.10)$$

where $\varepsilon_t^4 \sim \mathcal{N}(0, \sigma_{\varepsilon^4}^2)$. Unlike the other data series used, Form SLT flows data are available only beginning with January 2012. The surveys were also taken in October and December 2011, but January is the first consecutive month in which the stocks were measured, which is necessary for measuring monthly flows.

- **Annual Form SHL flows:** \hat{f}_t^{SHL} . The annual SHL stock surveys yield measures of annual flows, in much the same manner that the SLT surveys measure the stock at the monthly frequency. I model the SHL flows as the sum of both o_t and v_t over the year, but I assume that the SHL flows are accurate, so there is no error. This follows the literature on cross-border flows and reflects economists' assessment of the quality of the data, discussed in greater detail in Section 3.2.1. Mathematically, SHL flows are modeled according to

$$\hat{f}_t^{SHL} = \sum_{j=0}^{n^y-1} o_{t-j} + \sum_{j=0}^{n^y-1} v_{t-j}, \quad (3.11)$$

where n^y is the number of trading days in the year, which varies year-to-year.

Note that, unlike in Equation (3.3), I do not include any exogenous explanatory variables X_t in any of the relationships. While, in principle, I do want to control for

other variables, particularly in the daily asset pricing relationships, I do not because of data limitations. Most candidate control variables, such as inflation or economic activity variables, are not observed at the daily frequency, and so their inclusion is difficult and would, in any case, not induce day-to-day variation in asset prices.

These six relationships will form the measurement equation in the state space model, which I will discuss next.

3.3.3 State Space Representation

In order to implement the Kalman Filter, I must cast the model in state space form. Of course, the state space form consists of a measurement and a transition equation. The measurement equation was rationalized one relationship at a time in the section immediately above, so I will now rationalize the transition equation before formally writing down the model.

I specify a standard transition equation, modeling the two unobserved components of flows as autoregressive of lag order one. Given the apparent noisiness both of monthly measures of outright purchases and of daily Treasury price changes (and thus valuation changes), a more complicated lag structure does not appear necessary. I assume the error terms of the AR(1) models are identically and independently Gaussian.

These assumptions, together with Equations (3.6)-(3.11) from Section 3.3.2, yield

a state space model comprised of a measurement equation given by

$$y_t = Z_t \alpha_t + \varepsilon_t$$

$$\underbrace{\begin{bmatrix} \hat{v}_t \\ \Delta i_{5,t} \\ \Delta \log(e_t) \\ \hat{o}_t^S \\ \hat{f}_t^{SLT} \\ \hat{f}_t^{SHL} \end{bmatrix}}_{y_t \quad 6 \times 1} = \underbrace{\begin{bmatrix} 0 & 0 & \dots & 0 & | & 0 & 0 & \dots & 0 & || & 1 & 0 & \dots & 0 & | & 0 & 0 & \dots & 0 \\ \beta_1 & 0 & \dots & 0 & | & 0 & 0 & \dots & 0 & || & 0 & 0 & \dots & 0 & | & 0 & 0 & \dots & 0 \\ \beta_2 & 0 & \dots & 0 & | & 0 & 0 & \dots & 0 & || & \beta_3 & 0 & \dots & 0 & | & 0 & 0 & \dots & 0 \\ 1 & 1 & \dots & 1 \text{ or } 0 & | & 0 & 0 & \dots & 0 & || & 0 & 0 & \dots & 0 & | & 0 & 0 & \dots & 0 \\ 1 & 1 & \dots & 1 \text{ or } 0 & | & 0 & 0 & \dots & 0 & || & 1 & 1 & \dots & 1 \text{ or } 0 & | & 0 & 0 & \dots & 0 \\ 1 & 1 & \dots & 1 & | & 1 & 1 & \dots & 1 \text{ or } 0 & || & 1 & 1 & \dots & 1 & | & 1 & 1 & \dots & 1 \text{ or } 0 \end{bmatrix}}_{Z_t \quad 6 \times 502}$$

$$\times \underbrace{\begin{bmatrix} o_t \\ o_{t-1} \\ \vdots \\ o_{t-250} \\ \hline v_t \\ v_{t-1} \\ \vdots \\ v_{t-250} \end{bmatrix}}_{\alpha_t \quad 502 \times 1} + \underbrace{\begin{bmatrix} 0 \\ \varepsilon_t^1 \\ \varepsilon_t^2 \\ \varepsilon_t^3 \\ \varepsilon_t^4 \\ 0 \end{bmatrix}}_{\varepsilon_t \quad 6 \times 1},$$

and a transition equation given by

$$\alpha_t = T\alpha_{t-1} + \eta_t$$

$$\underbrace{\begin{bmatrix} o_t \\ o_{t-1} \\ \vdots \\ \overline{o_{t-250}} \\ v_t \\ v_{t-1} \\ \vdots \\ v_{t-250} \end{bmatrix}}_{\alpha_t \quad 502 \times 1} = \underbrace{\begin{bmatrix} \rho_1 & 0 & \cdots & 0 & 0 & || & & \\ \hline & & & & \vdots & & 0_{251 \times 251} & \\ & I_{250 \times 250} & & & \vdots & & & \\ & & & & 0 & & & \\ \hline & & & & & \rho_2 & 0 & \cdots & 0 & 0 \\ & & & & & \hline & 0_{251 \times 251} & & & & & \vdots & \\ & & & & & & I_{250 \times 250} & & & \vdots & \\ & & & & & & & & & 0 \end{bmatrix}}_{T \quad 502 \times 502} \quad (3.13)$$

$$\times \underbrace{\begin{bmatrix} o_{t-1} \\ o_{t-2} \\ \vdots \\ \overline{o_{t-251}} \\ v_{t-1} \\ v_{t-2} \\ \vdots \\ v_{t-252} \end{bmatrix}}_{\alpha_{t-1} \quad 502 \times 1} + \underbrace{\begin{bmatrix} \eta_t^1 \\ 0 \\ \vdots \\ 0 \\ \overline{\eta_t^2} \\ 0 \\ \vdots \\ 0 \end{bmatrix}}_{\eta_t \quad 502 \times 1} .$$

In both the measurement and transition equations, the vertical and horizontal double lines correspond to the break between the 251st and 252nd column or row, respectively. They divide the matrices and vectors into the components corresponding

to the outright purchases series, o_t , and the valuation change series, v_t . There are 251 elements of each of the two series in the state vector α_t because there are at most 251 trading days in a year, meaning that the SHL flows, \hat{f}_t^{SHL} , are the sum of at most the 251 most recent realizations of both o_t and v_t . Because some years have fewer trading days, each sum may be comprised of fewer than 251 elements, hence the “1 or 0” entries on the last line of Z_t . Similarly, the vertical lines in Z_t mark the first 24 columns that correspond to either o_t or v_t , reflecting the fact that there are at most 24 trading days in any month in the sample. Again, some months have fewer than 24 trading days, giving rise to the “1 or 0” entries in the fourth and fifth rows.

As this discussion suggests, the measurement equation varies depending upon data availability. If, on day t , some data series are not available, then the measurement equation, (3.12), is replaced by

$$y_t^* = Z_t^* \alpha_t + \varepsilon_t^*,$$

where starred variables denote the base variable with any row corresponding to missing data deleted. So, for example, if day t is not the last day of any month, then only daily data are observed, and so the measurement equation consists of only the first three rows of Equation (3.12). If t is the last day of the month so that Form S transactions are also observed, but neither the SLT or SHL data are observed, then the measurement equation consists of the first four rows of Equation (3.12). The transition equation is time-invariant.

Given the assumptions on the six scalar error terms, the vector errors can be

described as $\varepsilon_t \sim iid\mathcal{N}(0, H_t)$ and $\eta_t \sim iid\mathcal{N}(0, Q)$, with

$$H_t = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_{\varepsilon^1}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_{\varepsilon^2}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_{\varepsilon^3}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{\varepsilon^4}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{6 \times 6}, \text{ and}$$

$$Q = \left[\begin{array}{cccc|cccc} \sigma_{\eta^1}^2 & 0 & \cdots & 0 & & & & \\ 0 & 0 & \ddots & 0 & & & & \\ \vdots & \ddots & 0 & \vdots & & & & \\ 0 & 0 & \cdots & 0 & & & & \\ \hline & & & & \sigma_{\eta^2}^2 & 0 & \cdots & 0 \\ & & & & 0 & 0 & \ddots & 0 \\ & & & & \vdots & \ddots & 0 & \vdots \\ & & & & 0 & 0 & \cdots & 0 \end{array} \right]_{502 \times 502}$$

3.3.4 Kalman Filter

To this state space model, I apply standard Kalman filtering techniques, which are discussed in greater detail in Harvey (1989) and Hamilton (1994). I will review them here briefly for clarity and to explain the three different estimates of stocks and flows which will be discussed in Section 3.4. The last of three estimates is not discussed by Harvey or Hamilton and arises because I am interested in obtaining both flows *and* stocks from the same state space model. I generate this third series as do Stock and Watson (1989).

I begin with an initial guess for α at time one and the variance-covariance matrix for α at time 1. Reflecting the fact that these initial guesses are not conditional on

any data from the sample, these initial values are typically named $\alpha_{1|0}$ and $P_{1|0}$.¹⁰ Given these initial values, I produce the “filtered” estimates of α_t and P_t , denoted $\alpha_{t|t}$ and $P_{t|t}$, by recursively applying the updating equations given by

$$\alpha_{t|t} = \alpha_{t|t-1} + P_{t|t-1} Z_t' F_t^{-1} (y_t - Z_t \alpha_{t|t-1})$$

$$P_{t|t} = P_{t|t-1} - P_{t|t-1} Z_t' F_t^{-1} Z_t P_{t|t-1},$$

where

$$F_t = Z_t P_{t|t-1} Z_t' + H_t$$

and the prediction equations given by

$$\alpha_{t|t-1} = T \alpha_{t|t}$$

$$P_{t|t-1} = T P_{t|t} T' + Q.$$

This filtering process yields a series of vectors $\alpha_{t|t}$ for each date t in the sample. On any given date t , the filtered estimate $\alpha_{t|t}$ is a vector containing both components of Treasury flows on date t (and the previous 250 days) conditional on all data as of date t .

The filtered estimates are of little independent interest because using $\alpha_{t|t}$ to generate measures of flows and stocks mixes information sets. To see this, note that one might take the daily flows on each day t conditional on the information available as of that day to arrive at “filtered flows.” Accumulating these filtered flows yields the “filtered stock.” The filtered stock, which I will denote $s_{t|t,t-1,\dots}$, is given by

$$s_{t|t,t-1,\dots} = f_{t|t} + f_{t-1|t-1} + f_{t-2|t-2} + \dots f_{1|1} + s_0.$$

¹⁰For the results in this paper, I follow convention and choose $\alpha_{1|0}$ to be a vector of zeros and $P_{1|0}$ to be a diagonal matrix with all diagonal elements equal to 1,000, but the results are not sensitive to this choice.

This filtered stock variable is undesirable because it is the accumulation of each day's flow, where each one is conditional on a different information set. Because of this difficulty in accumulating the filtered stock, I will introduce a new series, the “iteratively smoothed” flows and stocks shortly.

In any event, I take the filtered estimates of $\alpha_{t|t}$ and $P_{t|t}$, run the Kalman smoother, and produce the “smoothed” estimates, denoted $\alpha_{t|T}$ and $P_{t|T}$. These smoothed estimates are produced by recursively applying the smoothing equations given by

$$\begin{aligned}\alpha_{t|T} &= \alpha_{t|t} + P_{t|t}T'P_{t+1|t}^{-1}(\alpha_{t+1|T} - T\alpha_{t|t}) \\ P_{t|T} &= P_{t|t} + P_{t|t}T'P_{t+1|t}^{-1}(P_{t+1|T} - P_{t+1|t})P_{t+1|t}^{-1}TP_{t|t},\end{aligned}$$

beginning with the last filtered α and P , $\alpha_{T|T}$ and $P_{T|T}$. This smoothing process produces the smoothed flows and stocks in much the same way as the filter does, except that all estimates are conditional on the same information set: the full sample (hence the $t|T$ subscript).

To address the issue of inconsistency in the information set with the filtered stock series, I also generate an iteratively smoothed series for both flows and stocks (Stock and Watson (1989)). These series are produced by running the Kalman smoother beginning at each date t . Of course, the iteratively smoothed series and the smoothed series will be identical at time $t = T$. This process of iterative smoothing produces, at date t , an estimate of all flows from time 0 to t conditional on the information set at time t . By accumulating these iteratively smoothed flows, I arrive at an estimate of the stock conditional on information at time t , called $s_{t|t}$, and expressed as

$$s_{t|t} = f_{t|t} + f_{t-1|t} + f_{t-2|t} + \dots f_{1|t} + s_0.$$

This notion of the stock of foreign holdings is conditional on only the current information set, and thus overcomes the inconsistency inherent in the filtered series.

Note, however, that changes in the iteratively smoothed stock from time t to $t + 1$ will reflect both the estimate of flows on date $t + 1$ and revisions to the estimates of history based on the new data that arrives at $t + 1$:

$$s_{t+1|t+1} - s_{t|t} = f_{t+1|t+1} + (s_{t|t+1} - s_{t|t}).$$

On most days, the changes in the information set are small and so this distinction is irrelevant, but on days when annual SHL surveys arrive, the revisions of history can be substantial. These large revisions reflect the fact that the annual surveys contain a great deal of information.

Finally, I must discuss the estimation of the eleven unknown parameters in Z_t , H_t , T , and Q . Up to this point in discussing the Kalman filter, I have assumed that these parameters are known, but of course they are not. I estimate the parameters by maximum likelihood, maximizing the log-likelihood function given by

$$l = -\frac{T}{2} \log(2\pi) - \frac{1}{2} \sum_{t=1}^T [\log |F_t| - (y_t - Z_t \alpha_{t|t-1})' F_t^{-1} (y_t - Z_t \alpha_{t|t-1})].$$

3.4 Results

In this section I will discuss the results, focusing first on the behavior of the series that I estimate, then comparing these series to the existing raw data and the BT data. In short, the smoothed estimate of flows behaves quite reasonably, though the daily outright purchases series may vary less than one would expect, perhaps owing to problems of econometric identification. My smoothed estimates also behave well in relation to other measures of flows, appearing less noisy than the Form S and BT series. My results suggest that both the BT series and the newer Form SLT series are fairly accurate measures of monthly flows, though there are a few notable discrepancies between our series. Form SLT data appear to estimate substantially

different valuation changes on a couple of occasions.

3.4.1 Estimated Latent Series

The smoothed estimates of cross-border Treasury flows and stocks appear reasonable on the basis of existing data. While we obviously cannot observe true flows or stocks, and thus cannot know how far the smoothed series are from the truth, they would appear quite close. Figure 3.1 depicts several measures of flows and Figure 3.2 depicts the corresponding stocks, both at the monthly frequency. The smoothed flows and stocks are, by construction, consistent with the annual SHL surveys of the stock of foreign holdings, believed to be the most accurate source of data on such holdings. The series reflect the general intra-year trends measured by the Form S surveys, but of course the Form S surveys do not include valuation adjustments. Figure 3.2 shows that the stocks of foreign holdings implied by accumulating Form S transactions forward from the most recent survey are very inaccurate. This inaccuracy reflects both a lack of valuation adjustments and also apparent error in the measured transactions or outright purchases. See Bertaut and Tryon (2007) for a more complete discussion of these issues with the TIC data. Both smoothed series conform well with the Bertaut and Tryon data, as well as with the TIC Form SLT data.

Examining the iteratively smoothed flows series in Figure 3.3, it is clear that the annual SHL surveys contain a great deal of information. This is partly due to the fact I have assumed that the SHL data is accurate, which itself reflects my (and the profession's) belief that the SHL data contain a great deal of information. Recall that the iteratively smoothed flows can be expressed as

$$s_{t+1|t+1} - s_{t|t} = f_{t+1|t+1} + (s_{t|t+1} - s_{t|t}).$$

The months in which the iteratively smoothed series deviates substantially from the

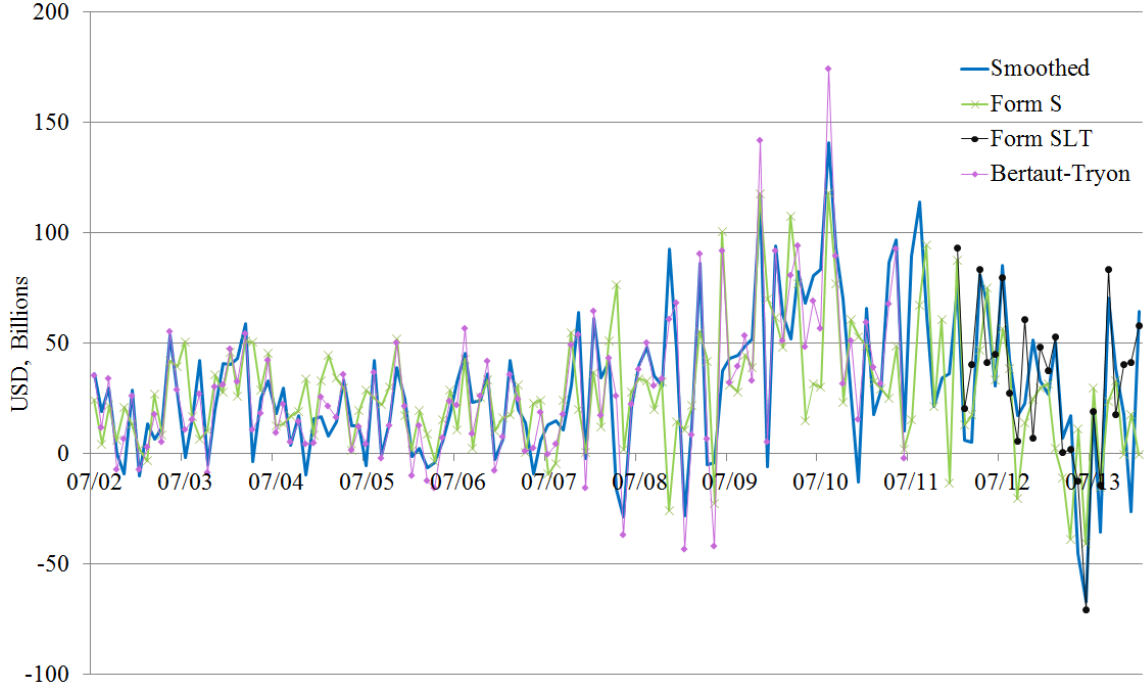


Figure 3.1: Cross-Border Treasury Flows at the Monthly Frequency by Various Measures. The plot shows smoothed flows, TIC Form S transactions, TIC Form SLT flows, and Bertaut-Tryon flows.

smoothed series are months in which the SHL survey is realized and the revisions to the assessment of daily flows over the past year (or the stock as of yesterday, the second term in the expression) are substantial. The picture is intuitively similar, though a bit more dramatic at the daily frequency, as the large revisions to history occur on individual days.

3.4.2 Behavior of Subcomponents of Flows

The subcomponents of Treasury flows, smoothed outright purchases, o_t , and valuation flows, v_t , generally behave as one might expect. The smoothed outright purchases series suggests that foreigners very rarely sell Treasuries back to American investors, but valuation flows regularly cause declines the value of foreign holdings of Treasuries. Nonetheless, both outright purchases, o_t , and valuation adjustments, v_t , induce substantial variability in Treasury flows at the monthly frequency (Figure 3.4). At the

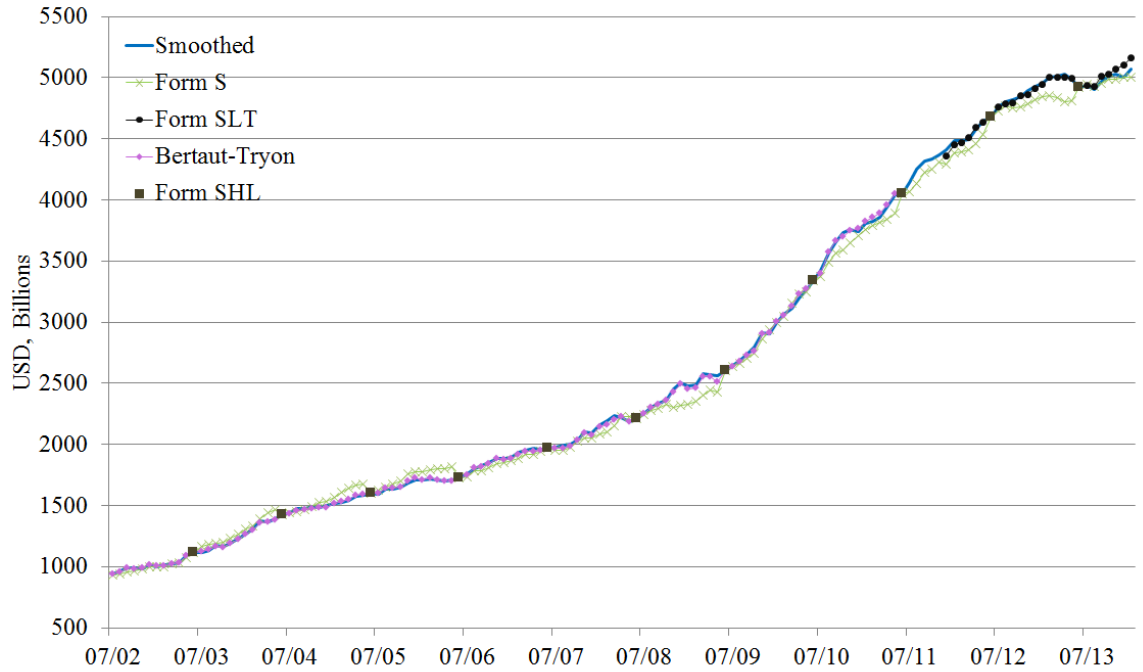


Figure 3.2: Stock of Foreign Treasury Holdings at the Monthly Frequency by Various Measures. The plot shows smoothed, TIC Form S transactions accumulated forward from most recent SHL stock survey, TIC Form SLT, Bertaut-Tryon, and TIC Form SHL.

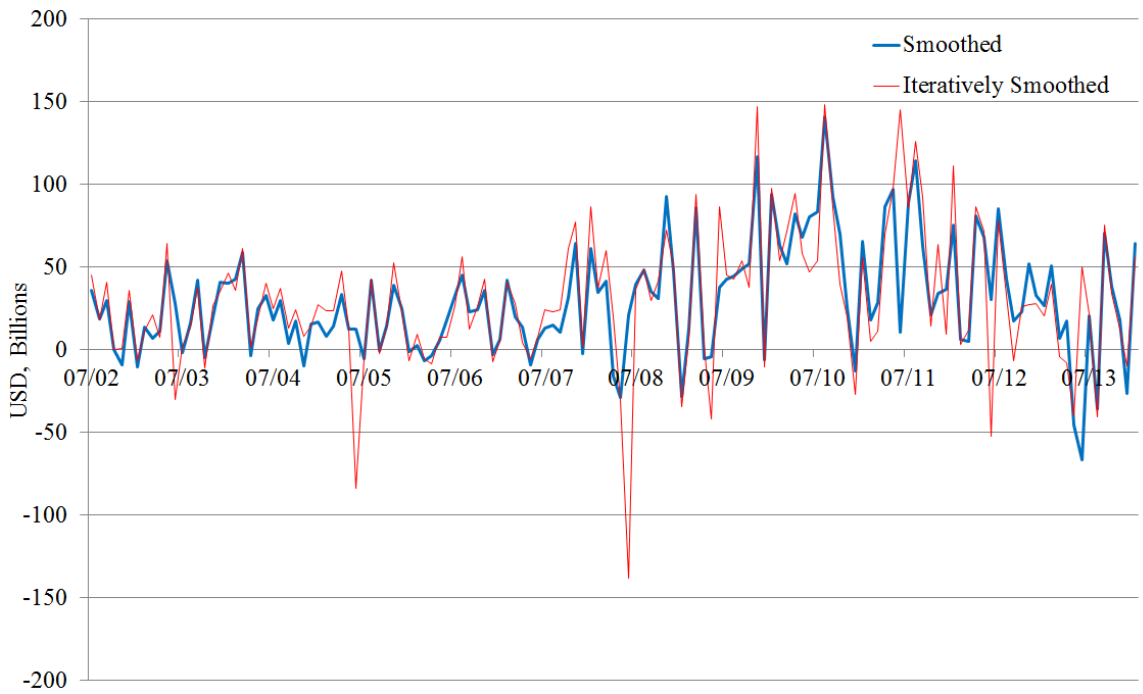


Figure 3.3: Cross-Border Treasury Flows at the Monthly Frequency, Smoothed and Iteratively Smoothed.

daily frequency, outright purchases are relatively smooth and valuation changes more volatile. Because outright purchases are persistent at the daily frequency, they still contribute meaningfully to monthly variation.

Assessing the plausibility of the valuation adjustment series at both the daily and monthly frequencies is straightforward and the series appear sensible. Given that we periodically observe the approximate duration of foreign holdings and we observe the daily changes in Treasury yields, we have a good idea of how valuation adjustments should behave at both frequencies. Indeed, the valuation change series is just the approximation based on duration and the five-year yield. The dramatic rise in the volatility of valuation adjustments in 2007 and 2008 reflects a combination of greater Treasury price volatility and larger foreign holdings of Treasuries (which would imply larger dollar changes in valuation for a given yield or price change).

Assessing the plausibility of outright purchases is more difficult, but the series also appear sensible. At the monthly frequency, we observe a noisy measure of outright purchases in the Form the TIC S survey. Figure 3.6 shows both outright purchases and the Form S transactions data. The outright purchases series is similar to the Form S series, though with the noise dampened, as the prior beliefs of analysts would suggest. Where the outright purchases series deviates from this baseline, it generally does so to maintain consistency with other measures of flows. For example, in between July 2012 and June 2013, Form S data substantially understated flows (as measured by the SHL data; see Figure 3.2) and did so to an extent greater than can be explained by valuation changes missing from the Form S data. Therefore, the outright purchases series generally exceeds the transactions data over the period. One notable deviation of the two series is in December 2013, when outright purchases are far higher than the transactions data. The smoothed total Treasury flows series is also higher than Form SLT data in December (Figure 3.8), though to a less dramatic extent. December was a month in which short yields rose significantly relative to the 5-year yield, suggesting

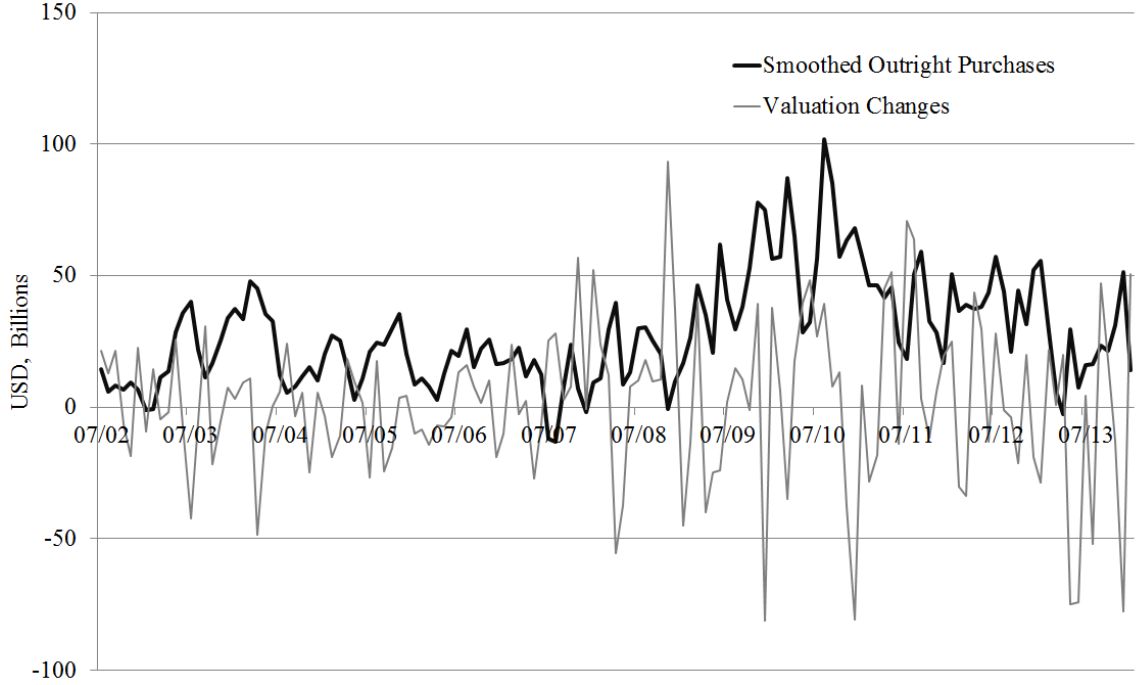


Figure 3.4: Monthly Smoothed Outright Purchases, $\tilde{o}_{t|T}$, and Valuation Adjustments, $\tilde{v}_{t|T}$.

the true capital loss on the foreign portfolio might be larger than I estimate, so that my valuation change might be overstated. However, it is unclear why an overstated valuation change would lead to overly positive outright purchases.

Data from the Japanese Ministry of Finance (MOF) provide a rare measure of daily purchases, which I use to confirm to the plausibility of the daily outright purchases series. Figure 3.7 shows daily smoothed outright purchases and MOF dollar purchases in 2003 and 2004, a period in which the MOF was especially active in foreign exchange markets. While the MOF purchases are often much larger than outright purchases on a given day, this is not a problem. First of all, the only series we observe at the daily frequency from the MOF are their dollar purchases, and these dollars were either invested in dollar deposit accounts or dollar securities. Further, not all of the securities were Treasuries and the breakdown by security type is unknown, though officials at the time indicated that the majority of their dollar securities holdings were Treasuries. Thus, the large MOF purchases on any given day might be invested

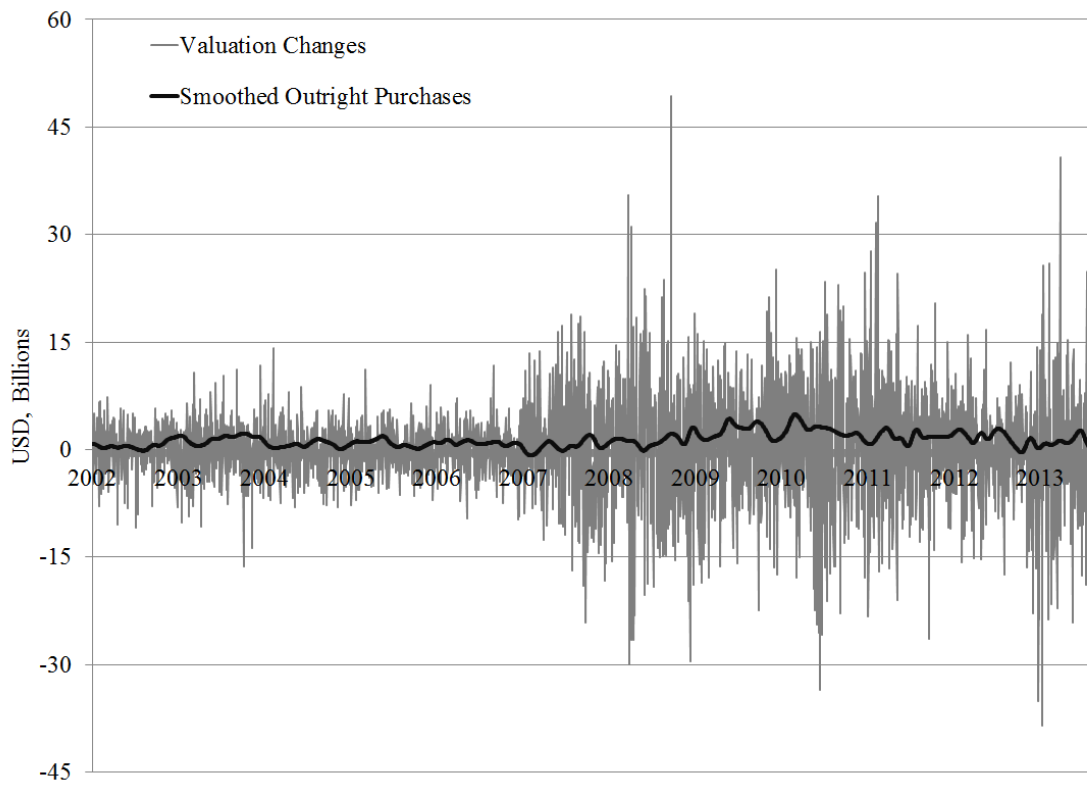


Figure 3.5: Daily Smoothed Outright Purchases, $o_{t|T}$, and Valuation Adjustments, $v_{t|T}$.

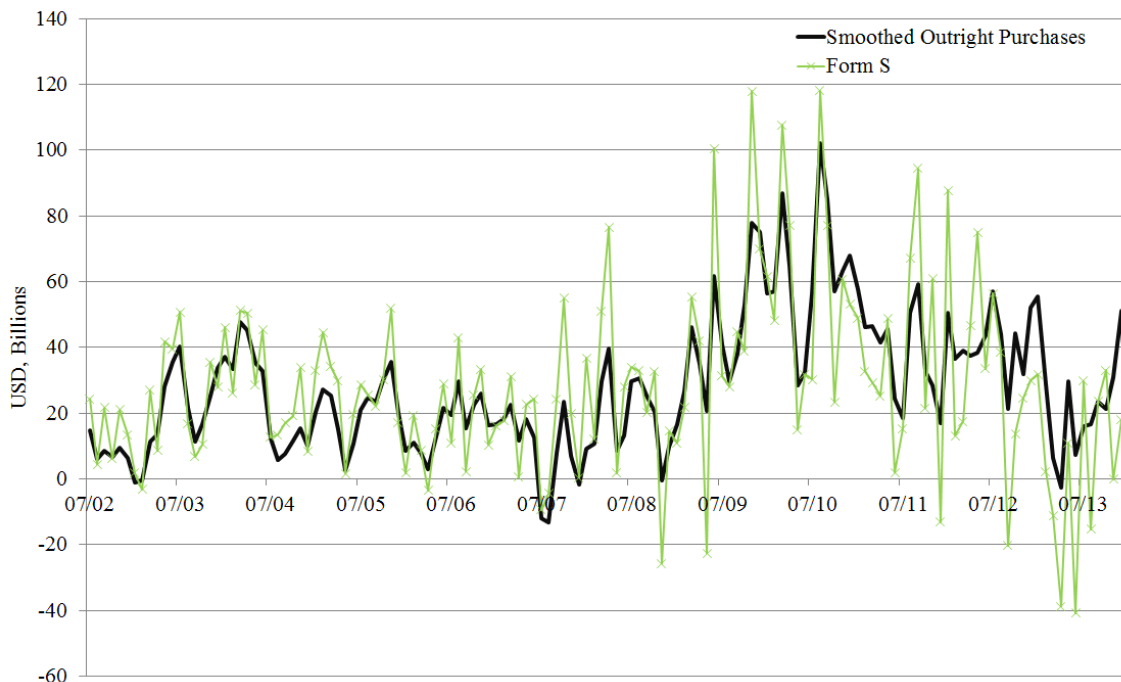


Figure 3.6: Smoothed Outright Purchases, $\tilde{o}_{t|T}$, and TIC Form S Transactions at the Monthly Frequency.

primarily in deposit accounts, resulting in smoother Treasury purchases (like the smoothed outright purchases series). This assertion is supported both by the MOF's stated policy of only gradually buying Treasuries to avoid causing market disruptions and by monthly data on the composition of MOF purchases in terms of deposits and securities. This data indicates that the MOF in fact did smooth their Treasury purchases relative to their foreign exchange interventions by depositing a large share of the dollars in deposit accounts, even at the monthly frequency. For example, about half of the dollars the MOF purchased between September 2003 and January 2004 were placed in deposit accounts. These deposit accounts were gradually reinvested in securities (presumably mostly Treasuries) through August 2004, even after dollar purchases ended in March 2004 (see Abe (2007) for more detail on this period). So, the persistent daily purchases of around \$2 billion of Treasuries from late 2003 through July and August of 2004 (as implied by the smoothed purchases series) are consistent with what data is available on daily foreign Treasury purchases. Thus, while it is

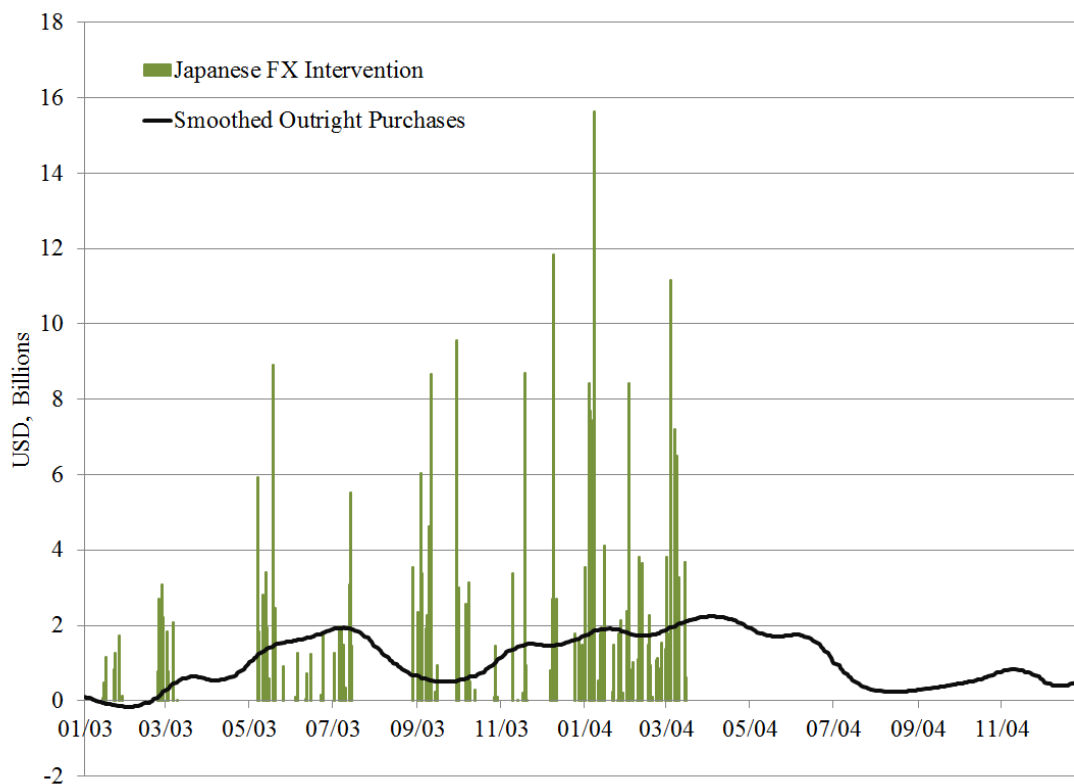


Figure 3.7: Daily Smoothed Outright Purchases and Japanese Ministry of Finance Purchases of USD. Data on Japanese purchases, denominated in yen, are available from the Bank of Japan. Purchases are converted to dollars using the daily nominal exchange rate, available from the Federal Reserve.

of course impossible to verify the accuracy of any one day's Treasury purchases, the daily outright purchases series appears reasonable.

3.4.3 Comparing Smoothed Flows with Existing Measures of Flows

As Figures 3.8 and 3.9 indicate, the smoothed flows series behaves well with respect to other monthly measures of flows. The series tend to move in similar fashions, and, as discussed in Section 3.2.2, my flows series exhibits slightly lower variance than the BT series. The BT data has a standard deviation of 33.3 while my series has a standard deviation of 31.3. As discussed previously, one might expect the BT

series to exhibit too much variation, as they include valuation adjustments on the accumulation of noisy measures of outright purchases. Thus, the BT series includes “valuation adjusted noise,” while my series should not, as the Kalman filter strips out this noise.

Nonetheless, there are a few cases where the series diverge from one another notably. For example, in November 2012, the smoothed and SLT series deviate noticeably, and it appears to arise mechanically because my smoothed outright purchases series substantially exceeds the Form S transactions. My smoothed series exceeds Form S transactions for most of that year, reflecting the fact that the Form SHL data and valuation changes suggest that the Form S series understated purchases over the period. To the extent that the Form S and SLT data are consistent with one another, they will both differ from my series. In any event, in the following month, SLT flows are substantially below my smoothed series, largely making up the difference. As another example, as noted above, the smoothed flows and SLT flows deviate substantially in December 2013, when short yields rose relative to 5-year yields. Because my valuation adjustment methodology relies exclusively on 5-year yields, it may be understating the capital losses on foreign holdings and thus overstating valuation flows. However, Figure 3.6 also shows that the smoothed outright purchases significantly exceed the Form S transactions. As noted in Section 3.4.2, the reason for this is unclear. A final episode of interest is the largely offsetting deviations of the smoothed and BT series in April and May 2009. This discrepancy is driven by the differing treatments of the noisy Form S transactions data between my method and the BT method. The Form S data show an unusually sharp swing from substantial net sales to substantial net purchases in April and May, respectively. This large swing feeds directly in the BT estimates, while the Kalman Filter interprets much of that variation as noise and smooths it out. As a result, this is the most striking episode in which the BT series exhibits more volatility than my series.

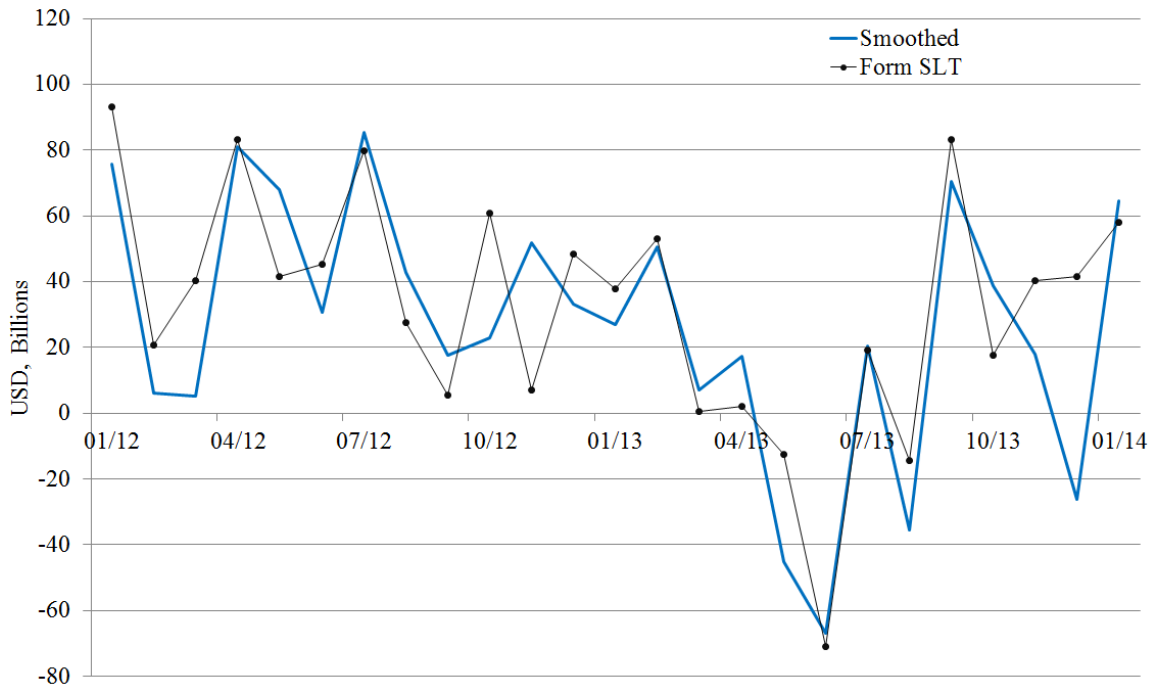


Figure 3.8: Cross-Border Treasury Flows at the Monthly Frequency, Smoothed and TIC Form SLT.

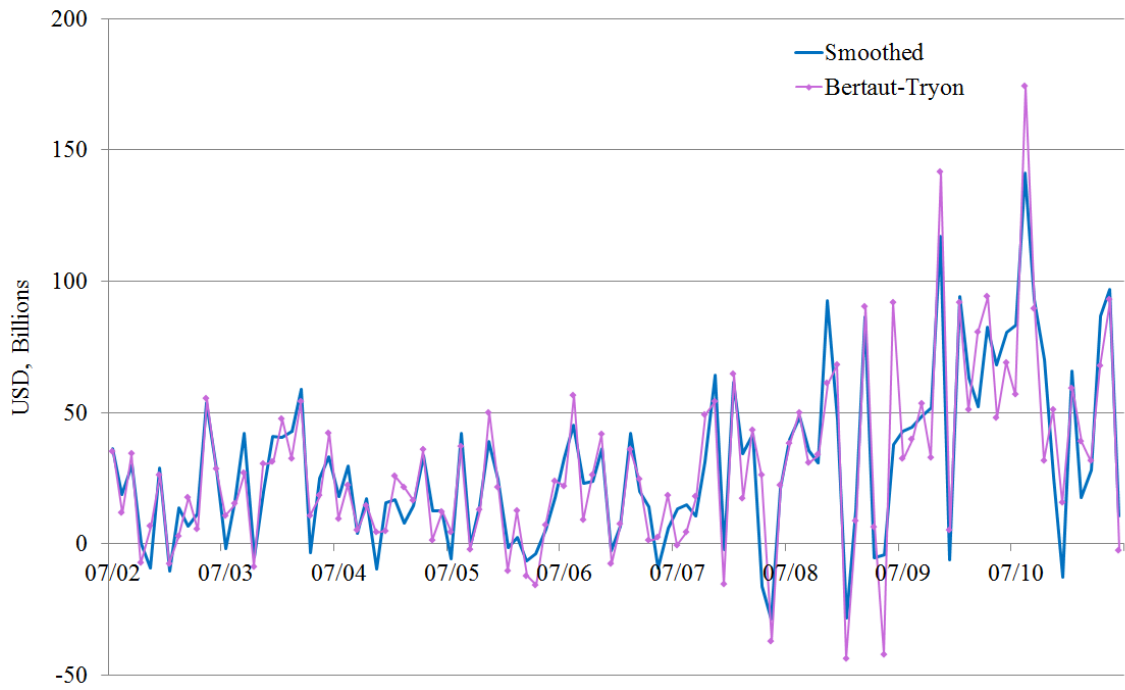


Figure 3.9: Cross-Border Treasury Flows at the Monthly Frequency, Smoothed and Bertaut-Tryon.

3.4.4 Coefficient Estimates

Finally, Table 3.1 presents the maximum likelihood estimates of the eleven coefficients of the model. All are statistically significant, reflecting the large sample size of daily data used to estimate such a small number of parameters. The coefficients on yield changes and log exchange rate changes, β_1 , β_3 , and β_3 , are smaller than might be expected, probably because of remaining problems with econometric identification. Particularly in the case of Treasury yields, it is difficult to disentangle the direction of causality between yield changes and flows/purchases, since these are essentially measures of price and quantity. As such, simultaneity issues arise which bias coefficient estimates toward zero. See the first two chapters of this dissertation for more discussion of these problems, as well as efforts to overcome them.

Coefficient	Estimated Value
β_1	9.8017×10^{-4} (1.3502×10^{-5})
β_2	-2.5540×10^{-5} (6.7419×10^{-7})
β_3	3.4155×10^{-5} (1.6148×10^{-7})
ρ_1	0.9899 (4.3224×10^{-5})
ρ_2	-0.0170 (4.2989×10^{-4})
$\sigma_{\varepsilon^1}^2$	0.0043 (2.1923×10^{-6})
$\sigma_{\varepsilon^2}^2$	1.0525×10^{-5} (1.2074×10^{-9})
$\sigma_{\varepsilon^3}^2$	103.4340 (0.0034)
$\sigma_{\varepsilon^4}^2$	100.7960 (0.0029)
$\sigma_{\eta^1}^2$	0.0326 (8.5910×10^{-5})
$\sigma_{\eta^2}^2$	73.6629 (0.0028)

Table 3.1: Maximum Likelihood Estimates of Model Coefficients. Asymptotic standard errors are given in parentheses. All coefficients are statistically significant at the 99% level.

3.5 Conclusion

This paper applies Kalman Filtering techniques to produce a new measure of cross-border Treasury flows using information from a larger number of data sources than have previously been used. The resulting series overcomes the widely known shortcomings of existing raw data and provides an alternative to the benchmark Bertaut and Tryon (2007) method for improving the data. I improve existing estimates of flows along two major dimensions. First of all, I provide estimates of flows which appear accurate even between high-quality annual surveys. Traditionally, raw data on Treasury flows has been viewed as very inaccurate, and competing sources of information conflict. The only previous solution for overcoming this inaccuracy produced a low-frequency (monthly) series which was based on a relatively limited information set and did not completely treat the noisy nature of the raw data. Second, I produce daily estimates of flows which appear plausible on the basis of economic intuition and what little was previously known about daily flows.

These data are useful for use by economists, both in academic research and policy analysis. While more accurate data is clearly and generally important, the daily flows series would be especially useful for use in high-frequency research such as event studies. Additionally, my results shed light on the accuracy of the relatively new Form SLT data from the US Treasury, suggesting that on a least one occasion, the SLT data was at odds with combined implications of other measures of flows.

Future research should address two remaining issues with the methodology of this paper. First, a wider measure of Treasury prices should, in principle, improve upon the estimates of valuation adjustments in this paper. While the precise nature of the valuation adjustment technique seems to make little difference most of the time, the discussion above highlighted at least one instance where unusual Treasury pricing behavior may have led my estimates of flows to deviate from other estimates. Second,

a robust identification scheme for the impact of purchases on yields and exchange rates would improve the information that the model can take from yield and exchange rate movements. Ultimately, this paper moves economists one step closer to observing true cross-border Treasury flows, a time series which has so far proven hard to measure.

Appendix A

Description of Events

- **July 21, 2005, 0600 CDT.** The PBOC announced that it was discontinuously appreciating the RMB versus the dollar by 2.1%. It also specified that the exchange rate would be allowed to float in a narrow range around the PBOC's target, and said that the target would be allowed to vary with an incompletely explained basket of currencies. The announcement was posted to the PBOC's website.
- **July 26, 2005, 0330 CDT.** A report was posted to the PBOC website downplaying the possibility of future appreciation of the RMB. The report was released in answer to market speculation that the initial policy shift meant more appreciation was soon to come. It clarified that the "gradualism" referred to in prior statements was intended to describe the reform of the RMB exchange rate regime, not necessarily quantitative changes in the exchange rate itself.
- **September 9, 2005, 1305 CDT.** A question and answer transcript from an interview of PBOC Governor Zhou Xiaochuan by a Chinese reporter was posted to the PBOC's website in which the governor indicated that the RMB would continue to gradually appreciate.
- **November 25, 2005, 0610 CDT.** The PBOC entered into a 12-month currency swap agreement with several state banks. The exchange rate on the 12-month swap was interpreted by the market as an indication of the exchange rate the PBOC expected to prevail in 12 months. The swap appears to have

been mentioned earlier, but the details of the swap, including the exchange rate, do not appear to have been released previously.

- **January 5, 2006, 0605 CST.** The director of the State Administration of Foreign Exchange (SAFE), which manages China's foreign exchange reserves, released a statement on SAFE's website suggesting that the administration intended to diversify its foreign currency holdings. Market participants interpreted the statement to mean that Chinese authorities intended to buy fewer dollars and dollar-denominated assets going forward.
- **November 10, 2006, 1450 CST.** Zhou Xiaochuan, Governor of the PBOC, told a reporter at a conference in Germany that the PBOC had no intention of selling any currencies, a statement that was intended to (and did) tell market participants that the PBOC planned to continue buying and holding dollars and dollar-denominated assets.
- **January 20, 2007, 0445 CST.** Chinese Premier Wen Jiabao said in a speech that China was looking for new ways to manage its foreign exchange reserves. Market participants, who were highly sensitive to indications about China's intentions regarding the US dollar, interpreted the statement to mean Chinese authorities were considering diversifying out of US dollars.
- **March 8, 2007, 2155 CST.** Chinese Minister of Finance Jin Renqing confirmed previous speculation that Chinese authorities were planning to establish a second investment company which would take some of the foreign exchange reserves managed by SAFE and invest them with a goal of higher returns. Given that SAFE maintained the investments primarily in safe, low-return assets and especially in US Treasuries, market participants interpreted this to mean that authorities intended to diversify away from Treasury securities.

- **March 15, 2007, 2235 CDT.** Chinese Premier Wen Jiabao said that the previously announced plans to create a new, higher-return investment company for foreign exchange reserves would be carried out so as to avoid affecting dollar-assets. This led market participants to expect larger Treasury holdings by China going forward.
- **March 20, 2007, 2150 CST.** An article was published summarizing an interview that day with PBOC Governor Zhou Xiaochuan. In it, the governor said that China did not intend to continue accumulating foreign exchange reserves. Taken at face value, this statement led participants to expect fewer Treasury purchases going forward. On the other hand, it was fairly quickly dismissed as a mistake or mistranslation.
- **November 6, 2007, 2120 CST.** The vice chairman of a Chinese government advisory body suggested that China should consider the value of currencies it purchased for foreign exchange reserves, suggesting a stronger euro might be a better currency to hold than a weaker dollar. This suggested that China may buy fewer dollars, but was a comment by a lesser official.
- **July 27, 2008, 0600 CDT.** In a statement released on its website after a quarterly monetary policy meeting, the PBOC said it aimed for policies to improve growth and also removed by-then-standard language describing its exchange rate mechanism as being market driven. Market participants interpreted this to mean that RMB appreciation was likely to slow going forward. As it turns out, this was the beginning of a nearly two year hold in the appreciation of the RMB.
- **March 23, 2009, 0210 CDT.** The deputy governor of the PBOC, Hu Xiaolian, told a reporter that China intended to continue buying Treasuries and that they were an important part of China's foreign exchange reserves. The press

conference occurred several hours earlier than 0210 CDT, but no earlier mention of the deputy governor's comments appeared on Bloomberg.

- **March 23, 2009, 0445 CDT.** An essay by Governor Zhou Xiaochuan was posted to the PBOC's website which stressed the need for a super-sovereign reserve currency. Market participants interpreted this to mean that the PBOC wanted an alternative to holding dollars. The release has since been removed from the PBOC's website, so the time is taken from the first Bloomberg article about the release.
- **June 26, 2009, 0450 CDT.** In its annual report on financial stability, the PBOC called for the creation of a super-sovereign reserve currency. This was interpreted by market participants as the PBOC officially taking the position expressed individually by Governor Zhou Xiaochuan in a March essay (see above). It reaffirmed the PBOC's desire for an alternative to the dollar. This release was also removed from the PBOC's website, so the timing is again from Bloomberg.
- **March 8, 2010, 2020 CST.** At a news conference, SAFE's Director Yi Gang reassured investors about China's Treasury purchases, saying that such purchases were mutually beneficial and indicating China intended to continue purchasing them. He also said China did not plan to diversify its holdings into gold. There were widespread recommendations at the time that China diversify away from dollar-assets.
- **April 8, 2010, 0355 CDT.** The *New York Times* reported that China was about to announce a change in its exchange rate policy. Given that it had maintained a nearly stable exchange rate since July, 27, 2008, market participants interpreted this to mean that the PBOC would allow a new round of RMB appreciation. The time is from a mention of the article on Bloomberg, as the

earliest timestamp on the *NYT*'s site is 0412 CDT. The story, which turned out to be several months too early, was apparently leaked just before publication.

- **April 12, 2010, 1955 CDT.** An article was published on Bloomberg summarizing a Xinhua article, published shortly before, discussing remarks made by Chinese President Hu Jintao to US President Barack Obama. President Hu remarked that China would choose the yuan's exchange rate for its own purposes, regardless of international pressure to do differently. He also commented that yuan appreciation would not resolve bilateral trade imbalances. Since he rarely remarked on currency matters, this was interpreted to mean China did not intend to allow much appreciation of the RMB over the near-term. The timing of the earlier Xinhua article could be determined, so the time is from Bloomberg.
- **May 10, 2010, 2015 CDT.** The PBOC posted its quarterly Monetary Policy Report on its website at 0430 CDT. The report contained a change in language suggesting that the PBOC intended to resume the appreciation of the RMB. The first mention of the new language Bloomberg was at 0716 CDT in reference to a note from Morgan Stanley. Wider discussion of the change in language is not seen on Bloomberg until 2015 CDT, following a China Business News article in which a PBOC adviser interpreted the language change to indicate future appreciation.
- **May 27, 2010, 0210 CDT.** SAFE posted on its website a rebuttal to a *Financial Times* editorial piece. SAFE denied allegations that it planned to shed some of its eurozone debt holdings. Market participants interpreted this to mean SAFE did not plan to shift toward dollar-assets.
- **June 19, 2010, 0600 CDT.** The PBOC posted a release to its website stating that it would resume RMB appreciation. The value of the RMB had been held

roughly constant since July 2008.

- **July 3, 2010, 0305 CDT.** Hu Xiaolian, a vice governor of the PBOC, said that exchange rate fluctuations were bad for China and that a country's current account balance is a good indication of whether a country's currency is at its equilibrium value. Since she also said that China's current account was nearing balance, these remarks were taken jointly to mean that the PBOC would likely not allow the RMB to appreciate rapidly over the near-term.
- **March 14, 2011, 2250 CDT.** Chinese Prime Minister Wen Jiabao said that Chinese authorities would continue to allow the RMB to appreciate gradually, partly to help control inflation.
- **October 11, 2011, 2040 CDT.** In a post on its website (which has since been removed), the PBOC refuted a bill just passed by the US Senate targeting China as a currency manipulator. In the post, the PBOC stated that it viewed the foreign exchange value of its currency as "reasonable" and that they would continue "gradual" currency reform. Based on discussion in the press, market participants appear to have taken this as news suggesting greater-than-expected appreciation of the RMB going forward.
- **February 3, 2012, 0305 CST.** Chinese Prime Minister Wen Jiabao made the strongest statements to date suggesting China was considering using its foreign exchange reserves to help address the eurozone debt crisis, both by supporting the IMF and through unilateral action. Should China use its reserves in this manner, it would likely require shifting some reserves out of dollar-denominated assets and Treasuries.
- **March 6, 2012, 0335 CST.** In an interview with the *Wall Street Journal* first published at the event time, Executive Vice President Wang Jiangxi of the

China Investment Corporation (CIC) said that CIC had recently had its assets boosted by \$30 billion transferred from SAFE and that CIC was working on a system that would allow CIC to grow steadily. Since CIC is an organization that manages the riskier, more diversified segment of Chinese foreign exchange reserves, this announcement would suggest fewer Treasury purchases should be expected.

- **March 11, 2012, 2245 CDT.** At an annual press conference, PBOC Governor Zhou Xiaochuan and other officials hinted that they believed the RMB was near its equilibrium level, which most market participants appear to have interpreted as suggesting a weaker-than-expected RMB going forward.
- **August 30, 2012, 0010 CDT.** Chinese Prime Minister Wen Jiabao, after meeting with German Chancellor Angela Merkel, reiterated China's willingness to invest in the European bond market, suggesting continuing euro purchases by Chinese official institutions and correspondingly fewer dollar and Treasury purchases.
- **May 6, 2013, 0605 CDT.** In a statement regarding a meeting of the Chinese State Council, Chinese Premier Li Keqiang made unusually specific remarks about plans to imminently liberalize RMB trading and make the currency fully convertible. Given the specificity of the remarks, market participants took this as a sign that the PBOC would allow the currency to appreciate further.
- **November 19, 2013, 0210 CST.** In a book released in conjunction with a Communist Party meeting, PBOC Governor Zhou Xiaochuan stated the PBOC's intentions to "basically" stop intervening in the foreign exchange markets routinely. While most of the remarks on the matter were repetition of earlier statements, they were viewed as more credible, as the Chinese president

and finance minister also contributed to and edited the book. These statements suggested further appreciation of the RMB.

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Curriculum Vitae

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